Effects of inclination of silty clay backfill on cantilever retaining wall with relief shelves

By

WASIM ABAS

NUST- 2018-MS-Geotech-00000274308

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

H-12 Sector, Islamabad, Pakistan

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(Thesis Supervisor)

Assistant Professor

NUST Institute of Civil Engineering (NICE)

THIS THESIS IS

DEDICATED

TO

MY BELOVED PARENTS

&

MY MOTHER (Late)

(For their endless love, support, and encouragement)

ACKNOWLEDGEMENT

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Abstract

For relief shelf supported cantilever retaining wall, the relief shelves are constructed monolithically with the wall and extended within the backfill material to increase wall's stability. Research shows that the provision of relief shelves reduces the intensity of influential parameters, such as lateral earth pressure, shear stress and wall top moment etc., on the wall which alternately increases its stability, economically. Several research studies are available in the literature, reporting the behavior of shelf supported retaining walls with levelled non-cohesive backfill. However, the research is insignificant in this context for inclined cohesive backfill. So, this study investigates a single and two shelves supported retaining wall with inclined silty clay backfill for lateral earth pressure, shear stress, wall top movement and base sliding. Several different combinations of inclined backfills are tested in the study, keeping water table at mid and top depth of the wall. A commercial software, Plaxis 2D was used to attain the set objectives. The test results show that the provision of relief shelves enables to increase the stability of cantilever retaining wall reducing its active pressure, overturning moment, shear stress and base sliding. The simple retaining wall relatively provides quite lower factors of safety than relief shelve supported retaining walls. The simple wall is even unable to provide safe factors of safety against sliding and overturning for levelled backfill, i.e., 0^o backfill inclination but the relief shelves supported walls are safe up to a backfill inclinations of 20 to 25^o. The test data shows that there are significant benefits to use relief shelves to strengthen the retaining wall of silty clay backfill. However, there is no efficacy to use backfill inclination beyond a certain angle as factors of safety initiate to decrease, which is associated with collapsing/destabilization of soil mass due to its higher inclination.

Chapter 1

1. INTRODUCTION

1.1 General

Retaining walls are essentially important in all infrastructure projects, such as bridges, slope stability, basement, roads and land use to resist the lateral earth pressure as the ground elevation supersedes the angle of repose of soil. Regarding this, various types of soils, such as cantilever, gravity, anchored, sheet pile retaining walls etc., are used. Gravity and gabion retaining walls are generally used but these are bulky in size. A situation arises in the field to construct high rise retaining walls, for which gabion and gravity retaining walls are not feasible due to their higher space requirement and economical aspects. A cantilever retaining wall is considered the best choice in such situations. Numerous researches have been conducted to innovate methods and approaches to enhance the stability of retaining walls on economic grounds which report that the retaining wall supported with counterfort wall, buttressed wall and shear key are the best options. However, one of the most effective methods is to construct the pressure relief shelves monolithically with the cantilever retaining wall and extend them within the backfill materials to increase the wall stability.

A cantilever retaining wall with pressure relief shelves is a special type of retaining wall (Figure 1.1). Various researchers reported that the provision of pressure relief shelves reinforced the backfill materials, reducing the intensity of lateral earth pressure on the wall, which ultimately reduced the size of the wall. **Padhye & Ullagaddi, (2011)** performed theoretical analysis on cantilever retaining wall with pressure relief shelves using Coulomb's theory and concluded that the active earth pressure was substantially reduced and as well as moment about the base, due to provision of shelves. Farouk, (2015) examined the variations in active earth pressure shelves supported retaining walls with non-cohesive backfills using Plaxis 2D and reported that single shelf at depth ratio (h1/H) of 0.30 decreased the bending moment up to 30% than simple cantilever retaining wall. Gupta & Pachpor, (2019) investigated the behavior of reinforced concrete cantilever retaining walls with single and double shelves using STAAD-Pro and concluded that the best location of relief shelf/shelves on retaining wall was observed at 7/12 of the height of wall for a single shelf, and at 7/12 and 4/12 of the height of wall for two shelves from the wall top.

The present research is most commonly dealt with shelf supported retaining walls with non-cohesive soil, and the concept of leveled backfill is most prevalent in these studies. There are certain situations in the field to use fine grained soil due to unavailability of non-cohesive soil in the close vicinity of the project area. In such situations, there is no option other than to use fine grained soil. Furthermore, in hilly terrains, an inclined backfill is also an integral part of retaining walls due to topographical profiles of the area, and in such situations, the stability of retaining wall is greatly associated with backfill inclination to withstand it without its rapture/failure.

The data regarding inclined cohesive backfill is insignificant in the literature. So, the novelty of this research work involves to investigate the lateral earth pressure, shear stress, wall top movement and base sliding of a single and two shelves supported retaining wall with silty clay backfill for several combinations of backfill inclinations. Plaxis 2D was used in the study to attain the set objectives. The analyses were carried out keeping the water table at mid and top height of the retaining wall. The test results show that the provision of relief shelves increases the stability of cantilever retaining wall reducing its active pressure, overturning moment, shear stress and base sliding. The retaining wall with single relief shelf (L_f = 0.4, W_f = 0.2 and t = 0.5 m) provides safe factors of safety; against overturning and sliding for backfill inclination up to 15°, and against bearing capacity for backfill inclination up to 20°, and for two relief shelves (L_f = 0.3 & 0.6, W_f =

0.2 and t = 0.5 m), it provides safe factors of safety against overturning, sliding and bearing capacity for backfill inclination up to 20°. The test results also show that there is no efficacy to use backfill inclination beyond a certain angle as factors of safety initiate to decrease, which is associated with collapsing/destabilization of soil masses due to higher inclination.

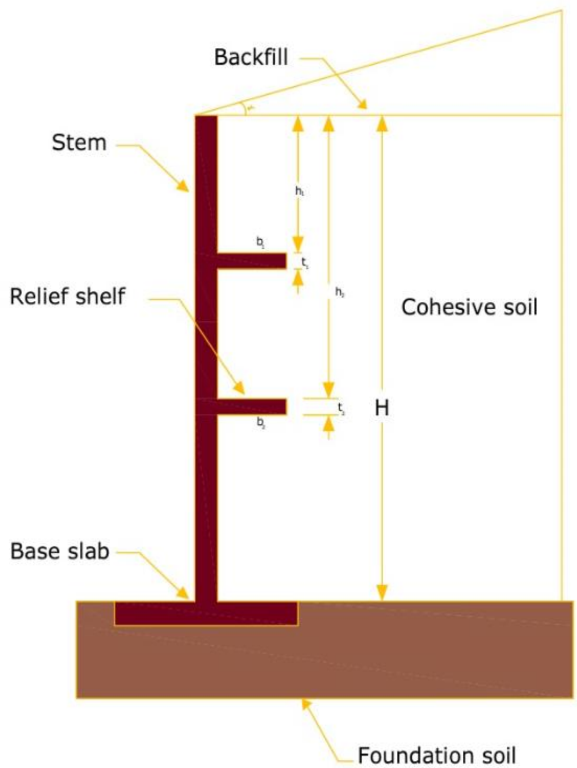


Figure 1. 1 Scheme of relief shelf supported retaining wall with inclined backfill

1.2 Objectives of the research work

To investigate the effects of inclination of silty clayey backfill materials for relief shelves supported cantilever retaining walls for various conditions using numerical simulation.

1.3 Justification of the research work

The research is quite useful in the context of Pakistan as Northern parts of the country contains hilly area with cohesive soils, and the retaining walls are most often supplemented with inclined cohesive backfills.

1.4 Contents of the thesis

Chapter 1 reports the precise summary of the research work.

Chapter 2 reports the literature review on the basis of previous work to proceed the current research

Chapter 3 discusses materials used and the methods applied to attain the set objectives of the study

Chapter 4 reports discussions on the test results of numerical simulation

Chapter 5 reports conclusions and a few key recommendations, drawn from the study.

Chapter 2

2. LITERATURE REVIEW

2.1 General

Reinforced cement concrete cantilever retaining walls are very common, specifically in mines, tunnels, roads and dams' projects to bear higher earth pressure of bulky backfills. Research shows that the provision of relief shelves to cantilever wall reduces its intensity of active pressure, base sliding, bending moments etc., and alternately provides a higher factor of safety economically and with less backfill space requirement than simple wall **(Types, 2019)**. Several types of retaining walls, such as gravity, cantilever, counterfort/buttressed, pre-cast concrete, anchored earth walls, sheet pile are common in practical applications. Concrete, stone and brick materials are used to construct the gravity retaining walls. Gravity retaining walls are self-supported walls and due to which they are thicker in cross-sections, and heavier in weight. The height up to 3 m height is suitable for such types of walls. The cross sections of these walls is greatly associated with the wall front, stability, method of construction and wall appearance **(Types, 2019)**.

A cantilever retaining wall is the most commonly used in the construction work due to its thinner size and higher stability. It consists of a vertical stem and a base slab which work as vertical and horizontal cantilevers under lateral earth pressure, respectively. Counterforts retaining walls are supplemented with counterforts at an appropriate interval. These counterforts decrease the bending moments in vertical walls of larger height, and are used in walls of 8 to 12 m height. The facing units are connected to rods or/and strips with their ends buried in the ground in anchored earthen walls. The anchors work in a similar fashion to that of abutments. High strength prestressed steel tendons are widely used for anchoring. Steel sheet pile walls are commonly used in slopes or excavations and constructed, driving steel sheets to the desired depths. Sheet pile walls have frequent use in water front buildings **(Types, 2019)**.

Research shows that cantilever retaining walls need lesser materials than other types of retaining walls. Furthermore, these walls can be constructed to larger height than gravity retaining walls to withstand high pressure. The stability of the walls is greatly associated with the weight of soil on heel of the wall **(Types, 2019)**.

2.2 Experimental, analytical and theoretical studies for shelf supported retaining walls

Patil & Wagh, (2010) performed analytical procedures to examine the behavior of a simple and shelves supported cantilever retaining. A model of cantilever retaining wall with specifications as in Table 2.1 was considered in the study. The test results showed that the shelves supported wall reduced the concrete volume and reinforcement steel up to 35%, and 18%, respectively than a simple wall.

Table 2. 1 Properties of retaining wall used in the model of Patil & Wagh (2010)

1	Height of cohesion-less backfill supported (h)	6 M
2	Unit weight of soil (Backfill)	19 KN /Cu. M.
3	Angle of internal friction (Backfill)	30^{0}
4	Bearing Capacity of soil (Foundation strata)	200 KN / Sq. M
5	Angle of wall friction with backfill	22^{0}
6	Angle of wall friction with foundation soil	25^{0}
7	Unit weight of reinforced cement concrete	25 KN /Cu. M.

Padhye & Ullagaddi, (2011) performed theoretical analysis on cantilever retaining wall with pressure relief shelves using Coulomb’s theory and concluded that the active earth pressure and bending moment substantially reduced with provision of shelves. The study further added that the lateral earth pressure was observed maximum for (45+∅/2) angle between the rupture surface and horizontal. **Farouk, (2015)** studied the total active earth pressure of shelves supported walls with non-cohesive backfill using Plaxis-2D-AE and reported that single shelf at depth ratio (h1/H) of 0.30 decreased the bending moment by about 30% than a simple cantilever retaining wall. Furthermore, the study suggested to use shelves with thickness ratio (t_s /b = 0.10), extending their widths beyond the rupture surface.

Guide & Student, (2015) simulated the pressure distribution of simple and shelves supported retaining walls using STAAD-Pro, and reported that maximum reduction in earth pressure was noted for locations of relief shelf at 0.4H to 0.5H. The study further added that the provision of relief shelf at 0.5H reduced the deflection by 41.50% than simple retaining wall. However, insignificant differences were noted with an increase in the width of relief shelf. **Krishnamurthy, (2016)** used commercially available finite element packages (SAP – 2000) to examine a cantilever retaining wall and reported that shelves supported cantilever retaining wall showed less moment than a simple wall. The study also added that the wall with pressure relief shelf at 2/3rd height of the wall from top provided more promising results than other depths. **Shehata, (2016)** evaluated the stability of retaining wall without relief shelf, single relief shelf and two relief shelves with varying width and thickness using Plaxis-2D and showed that the wall top movement and bending moment reduced significantly in shelf supported wall , which alternately increased the structural stability. The study also showed that the single relief shelf with location factor of 0.30 provided 30% less bending moment than a simple wall.

Chauhan & Dasaka, (2018) examined width and position of relief shelves for cantilever retaining walls and reported that the lateral thrust on retaining wall reduced up to 23% by using relief shelves.

Moreover, it was also noted that the maximum allowable width of different relief shelves was greatly dependent upon each other. **Chougule & Patankar, (2017)** executed the stability of simple, a single and two relief shelves supported reinforced retaining cantilever wall and showed that the best shelf location was at 7H/12 from top of stem for single relief shell, and for two relief shelves, the best locations were 7H/12 4H/12 from top of the stem.

Chauhan et al., (2019) investigated the possible reasons of failure of 10 to 13.9 m high of five relief shelves supported cantilever retaining wall with silty clay backfills. It was observed that a portion of wall about 20 m was collapsed after five years of its construction. FLAC 3D was employed to do the numerical analysis to explore the reason of this failure. Due to silty clay backfill, undrained condition was employed in the analysis. The details of retaining wall with relief shelf are shown in Figure 2.5.

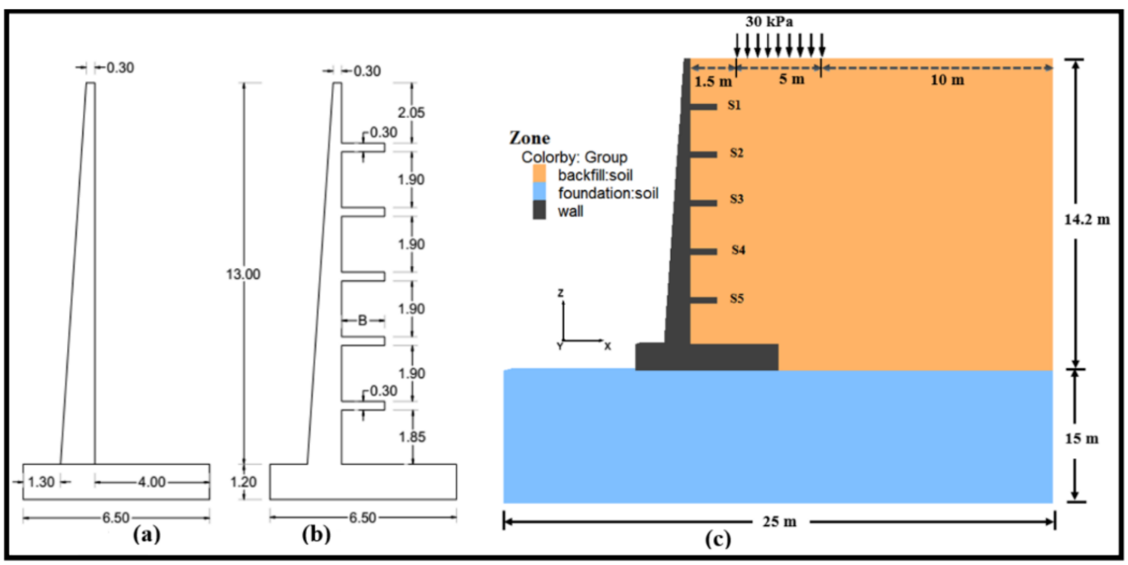


Figure 2. 1 Sectional dimensions of retaining wall (a) without relief shelf (b) with relief shelves and (c) numerical grid of rigid retaining wall with relief shelves

The test results showed that relief shelves reduced the lateral thrust from 33 to 38% and furthermore, the relief shelves with width of 1.2 m showed better results in context of deflection of the wall and deflection of relief shelves was also noted proportional to width of relief shelves. **Gupta & Pachpor, (2019)** examined the behavior of a single and two reinforced concrete cantilever retaining walls and concluded that the best location of relief shelf/shelves was observed at 7/12 of the height of wall from the top for a single shelf, and at 7/12 and 4/12 of the wall height from top for two shelves. **Chauhan et al., (2019)** studied the effectiveness of relief shelves on retaining walls employing FLAC 3D. In the study, 3 relief shelves with various combinations of location factor and width factor were used for 8 m high retaining wall. The study revealed that relief shelves with width factor ranging 0.3 – 0.8 reduced the lateral thrust on the wall from 11 to 26%. The shelves with width factor of 0.7 provided promising test results than other alternatives.

The stability of retaining wall is generally determined using factors of safety against overturning, sliding and bearing capacity failure. Different researchers reported to use different factors of safety for retaining wall. According to **(Akhtar & Jamadar, 2019)** 3.0, 2.0, and 1.5 are considered safe factors of safety against overturning, base sliding and bearing capacity, respectively. **(C.N.V Reddy, 2017)** investigated the stability of foundation in hilly areas and reported that foundation soil showed sufficient strength in dry state, however the strength was significantly less in saturated conditions. The study also added that the foundation and backfill soils played an important role to define the stability of retaining wall.

Manish & Acharya, (2019) used a case study of AANSON building at Sinamangal Kathmandu, Nepal to examine cantilever retaining wall with and without relief shelves. It was noted that the relief shelf of 1 m width at mid height of stem increased the factors of safety (FOS) against sliding from 1.36 to 1.96 which also reduced the moments along the stem up to 52.85%.

Bhusari & Ghodke, (2019) studied the effects of relief shelves with various combinations of location factor, width factor and thickness on stability of retaining wall and reported that the relief shelves provided bending moments up to 70% less than a simple retaining wall. The best location for a single relief shelf was found in-between 0.4H and 0.5H. The study suggested to increase the width of shelves gradually from top to bottom of the wall. Furthermore, two shelves with location factors 0.35H and 0.55H and width factors 1.5 m and 2 m from the top of wall provided better factors of safety against sliding and overturning than simple and single shelf walls. **Akhtar & Jamadar, (2019)** analyzed the influences of inclined backfills on the stability of simple and shelves supported retaining walls. The height of retaining wall was varied from 3.5 to 6 m in the study. It was added that the economic location for relief shelf was at 7H/12 and 6H/12 for uniform and inclined surcharges, respectively, and the factors of safety against overturning, sliding were 2.83 and 1.55 in case of retaining wall with single relief shelf, 3.86 and 2.6 in case of retaining wall with single relief and horizontal backfill and 3.83 and 2.42 in case of retaining wall with single relief shelf and inclined backfill respectively.

It was observed that different researchers used different approaches to examine the effects of relief shelves on the stability of retaining wall. Various combinations of relief shelves were employed in the studies. It was found that the provision of relief shelves resulted in a decrease in the influential parameters, such as lateral earth pressure, bending moment and sliding etc. The present work generally deals with levelled backfill of non-cohesive nature. The tests data is still lack in studying the effects of backfill inclinations on the stability of shelf supported retaining walls with silty clay backfill materials. So, this study examines the effects of silty clayey backfill materials on the stability of shelf supported retaining walls. Three cases i.e., simple cantilever retaining wall, single relief shelf and two relief shelves supported retaining walls were analyzed in this study for various backfill inclinations.

2.3 Plaxis 2D for numerical simulation

Plaxis is commonly used in geotechnical engineering to perform deformation and stability analysis in the fields of retaining walls, foundations, excavations, reservoir geomechanics, embankments, mining etc. Plaxis is a computer program, utilizes Finite Element Modeling (FEM) to do calculations. Most engineering institutions and organizations rely upon it for deformation and stability analysis because of its higher efficiency, results reliability, material models accuracy and tendency towards importing CAD files. It is available in market in three versions, i.e., Plaxis 2D, Plaxis 2D advanced, and Plaxis 2D ultimate.

2.3.1 Plaxis 2D

Plaxis 2D is used worldwide for deformation and stability analysis in soil and rock mechanics, which is not facilitated to simulate steady state ground water, consolidation analysis, and creep or thermal flow during analysis. It is a computer software that uses Finite Element Modeling (FEM) to perform the analysis.

2.3.2 Plaxis 2D advanced

Plaxis 2D advanced is facilitated with features to simulate the steady state ground water, consolidation analysis, creep or thermal flow conditions to enhance the geotechnical design capabilities of deformation and stability analysis. It does analysis at a faster rate than Plaxis 2D.

2.3.3 Plaxis 2D ultimate

Plaxis 2D ultimate deals with challenging geotechnical projects of utmost importance and functionality and it is facilitated with special features to simulate the effects of soil vibrations, time dependent variations and transient heat flow on mechanical and hydraulic behavior of soil.

2.4 Features of Plaxis 2D

Plaxis 2D has the potential to simulate the actual soil model using axisymmetric or plane strain conditions. It consists of four sub programs, i-) input program, ii-) calculation program, iii-) output program, and iv-) curves program. Figures 2.6 – 2.9 highlight few pictorial views of different steps, involved in the analysis of the program. Plaxis 2D starts by double clicking the icon in the input program. A create/project log box is opened which is used to select either to work on new project or an existing work (Figure 2.6). After the selection of new project, general settings window is opened showing title of file, model type i.e. plain strain or axisymmetric, 6-node or 15-node element, and others (Figure 2.7). The grid provides a matrix of dots. These dots are used as reference points. Grid spacing are used to determine the distance between points. To set the grid spacing, the grid box contains values. In the next stage, lines and plate element are generated to define the geometry of different elements. After creating the geometry, horizontal and vertical fixities are applied and interfacing values are applied to define the plate and soil elements connections (Figure 2.8). The material models are then defined in the model.

The next step is to define mesh generation selecting from very coarse to very fine meshing, and after then, pore water pressure and initial stresses are generated in the model. The program performs calculations in different stages which vary with respect to project type (Figure 2.9). For retaining wall, excavation is followed by construction of retaining wall and then putting back the backfill materials to excavated area**.**

Plaxis 2D avails plastic analysis, consolidation analysis, phi/c reduction and dynamic analysis to do the calculations. Calculations are performed in the output program of Plaxis 2D to get datasets for deformations, stresses, pore water pressures, bending moment, shear forces, velocities and accelerations etc. Finally, plots between displacement, pore water pressure, stresses and load etc., are plotted to examine the test data.

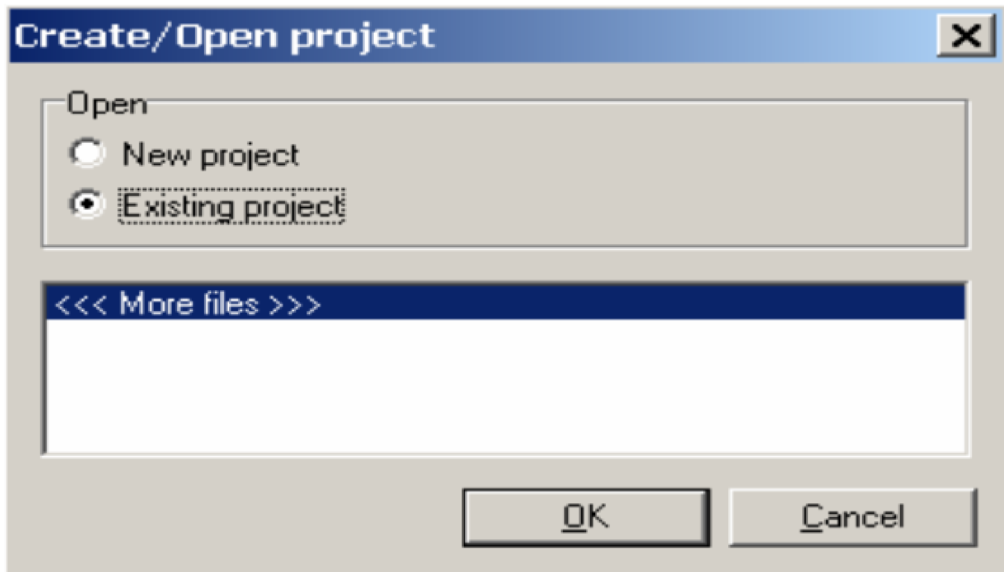


Figure 2. 2 Create/new project in Plaxis 2D

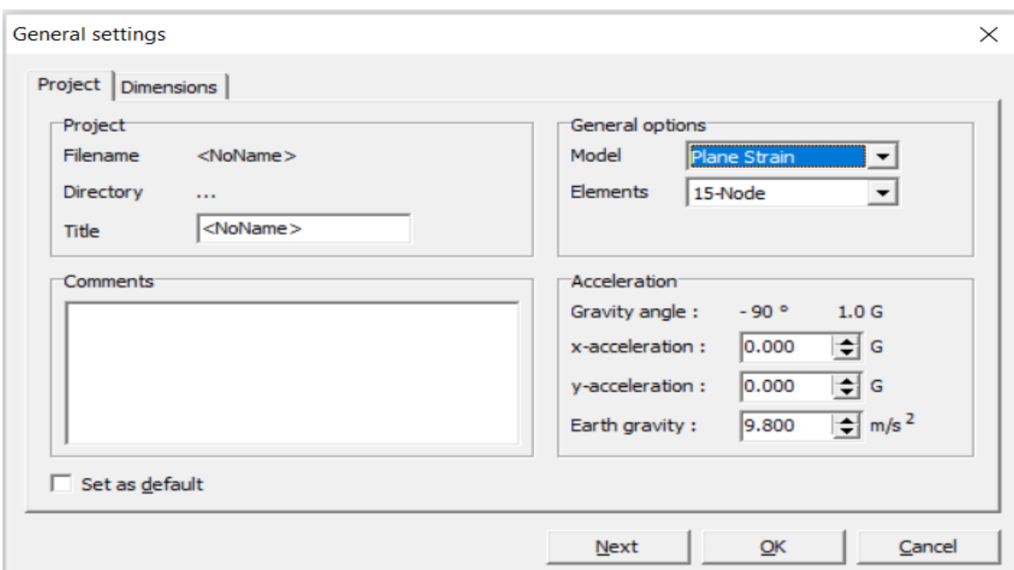


Figure 2. 3 General settings in Plaxis 2D

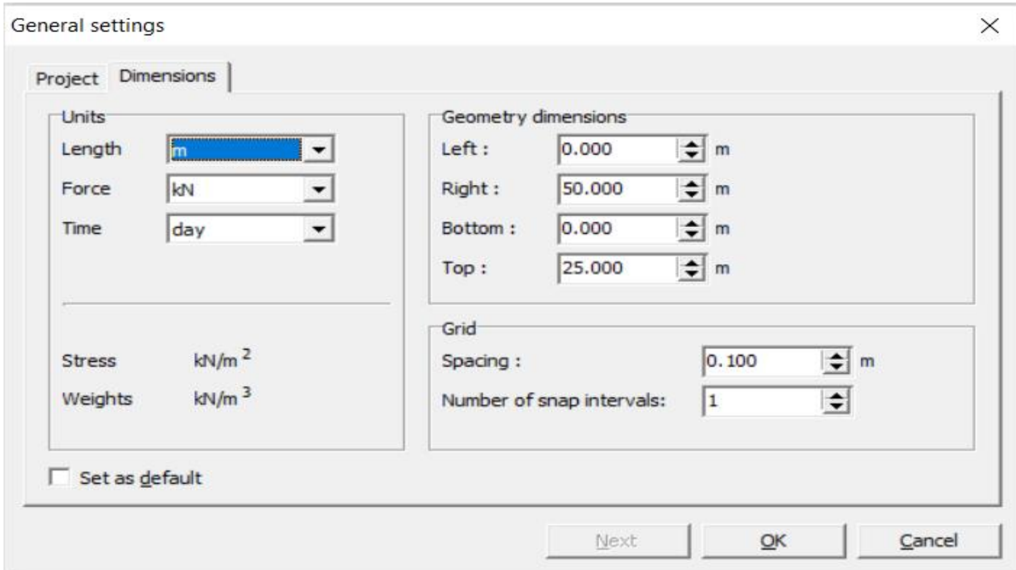


Figure 2. 4 General settings of dimensions in Plaxis 2D

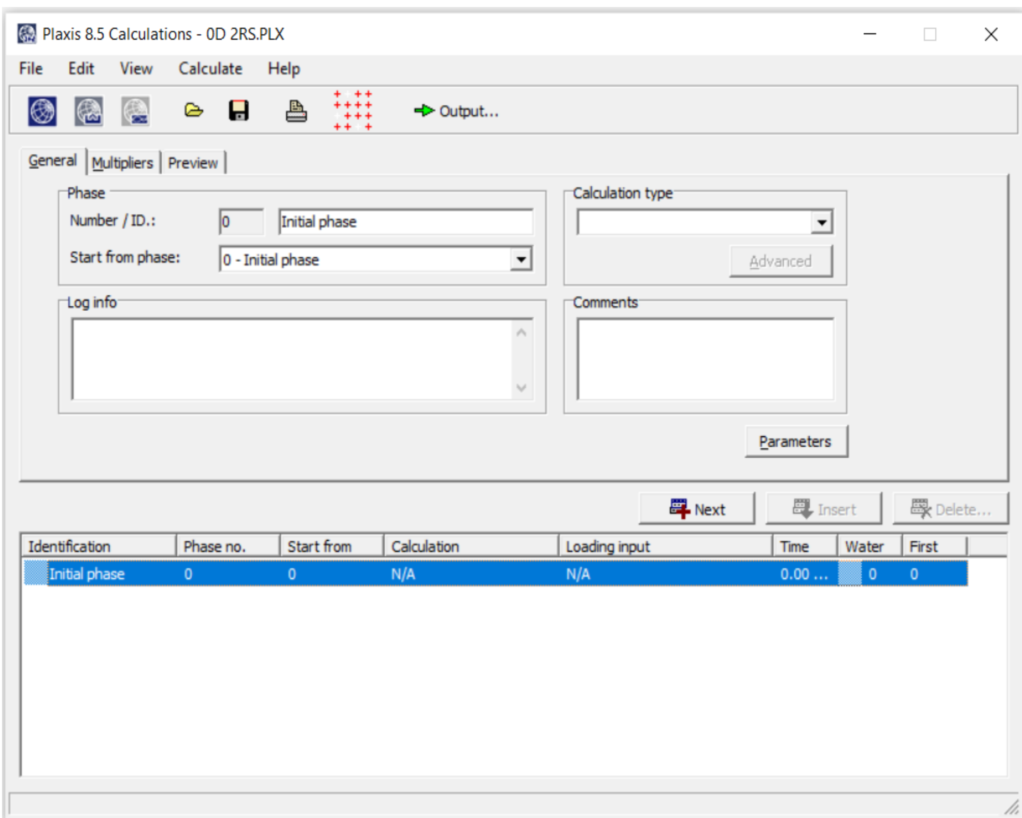


Figure 2. 5 Calculations program of Plaxis 2D

2.5 Material models used in finite element analysis

Soil and rock important attributes are analyzed using different material models in finite element analysis that includes, linear elastic model, Mohr- Coulomb model, soft soil model, hardening soil model, soft soil creep model, jointed rock mode, modified cam clay model, user defined model. Most researchers prefer to use Mohr-Coulomb and hardening soil model for deformation and stability analysis in soil and rock mechanics **(Çelik, 2017)**. The material properties of these models are relatively easy to determine from laboratory and field tests.

2.5.1 Mohr-Coulomb Model

Mohr Coulomb model is well known for its simplicity with wide application in engineering fields and it simulates the soil properties utilizing different parameters; such as soil elasticity with elastic modulus (E) and Poison's ratio (ν), soil plasticity with angle of internal (φ) friction and cohesion (c), and dilatancy with angle of dilatancy (ψ). The model uses a constant soil stiffness which increases linearly with depth, and which relatively makes the computations fast. The soils stiffness (E_{50}) remains constant within the elastic zone until the specimen fails. Generally, the true soil stiffness is not constant and changes with changes in stress level (Figures 2.10 and 2.11). A few limitations are also associated with the model that it over predicts and under predicts the ground movement against stress levels < 50% and > 50% of ultimate strength, respectively.

The model presumes that unloading reloading stiffness modulus is equal to loading stiffness, i.e., $E_{ur} = E_{50}$ during simulation but in actual practice, a soil provides quite stiffer modulus under unloading reloading conditions than under loading conditions. Various studies suggest to use unloading reloading stiffness 2 to 5 times higher than the loading stiffness, i.e., $E_{ur} \approx 2\sim5\ E_{50}$, so the higher value of E_{ur} is entered in the model than E_{50}. Despite these limitations, Mohr Coulomb model is widely used due to its ability of fast computations and first order estimations.

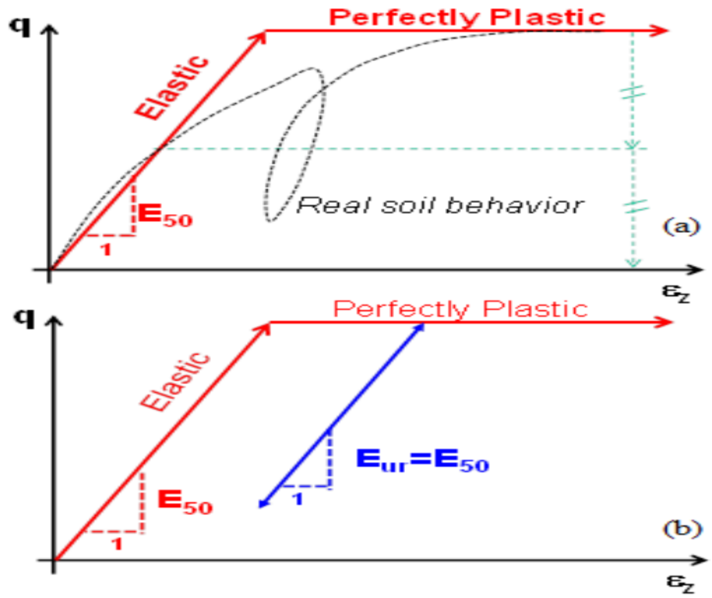


Figure 2. 6 Limitations in Mohr Coulomb model

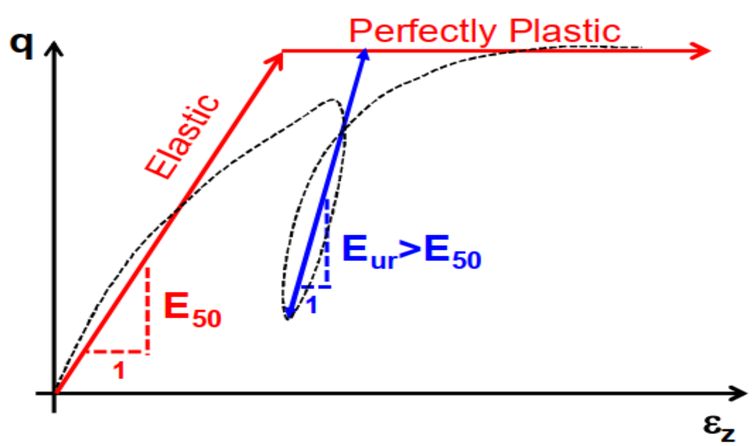


Figure 2. 7 Real soil behavior

2.5.1.1 Material properties

The parameters, such as Young's modulus, Poison's ratio, cohesion, angle of internal friction, dilatancy angle and unit weight are used in the model to simulate the soil behavior, which are determined from laboratory and field tests. Young's modulus defines the bending and stretching ability of materials, subjected to any force. Equations 1 and 2 highlights a mathematical expression of modulus of elasticity.

$$\text{Young's modulus} = \frac{Tensile\ stress}{Tensile\ strain} \qquad \text{(Equation-1)}$$

$$E = \frac{FL}{A*\Delta L} \qquad \text{(Equation-2)}$$

In these equations, E = Young's modulus in Pascal's (Pa),F = applied force, L = Initial length, A = square area, ΔL = change in length. Therefore, a steady value of stiffness modulus is used in the model to characterize soil's mechanical behavior. Poison's ratio is the ratio of vertical to horizontal deformation of materials. It is dimensionless parameters ranging from 0.1 to 0.45, however (**Brinkgreve et al., 2004)** reported to use Poisson's ratio between 0.15 and 0.25 for soil materials. For particular unloading conditions, the low values are used. The study also suggests to use Poisson ratio of 0.35 to simulate the undrained conditions under loading conditions in the model. Cohesion and angle of internal friction are important parameters used in the model to simulate the mechanical behavior of soil materials. Direct shear and triaxial compression tests are used to determine the cohesion and angle of internal friction of soils. Figure 2.12 shows the direct shear test results to determine the cohesion and angle of internal friction of a soil.

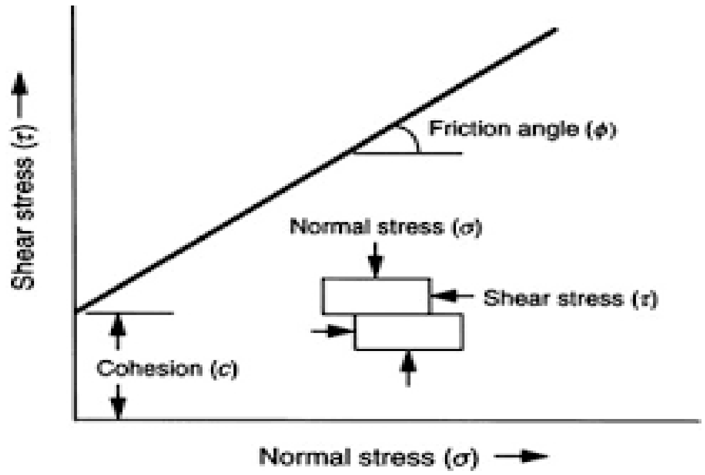


Figure 2. 8 Cohesion and angle of internal friction estimation from direct shear laboratory tests

Dilatancy is the ability of granular materials to undergo shear deformation under the applied loads, which depends on the angle of internal friction. For non-cohesive soils with angle of internal friction > 30^0, it is suggested to use dilation angle, i.e., $\psi = \varphi$-30°.

2.5.2 Hardening soil model

The hardening soil model (HSM) is a comprehensive elastoplastic fundamental model for modelling stiff and soft soil behavior. HSM simulates the plastic strain conditions under compressive loadings, relating stiffness characteristics to stress levels **(Likitlersuang et al., 2013)**. The model considers soil dilatancy, establishing a yield constraint. The elastic perfectly plastic is based on yield surface of the main stress zone, simulating the elastic behavior of soil and in contrast to this, the HSM's considers the plastic straining of the yield surface. It is clear from Figure 2.13 that the stiffness modulus shows a decreasing trend with an increase in stress level, showing a nonlinear behavior. The formulations of hyperbolic hardening soil model as in **(Likitlersuang et al., 2013)** are presented in Equations 3 - 5.

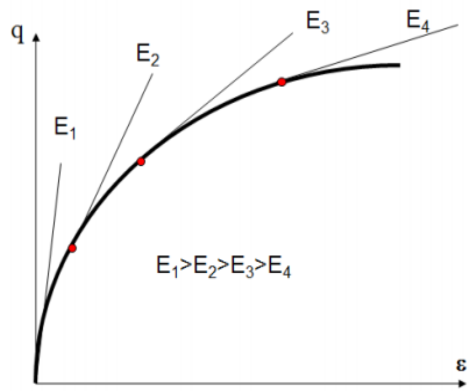


Figure 2. 9 Non-linear behavior of stiffness modulus for hardening soil model

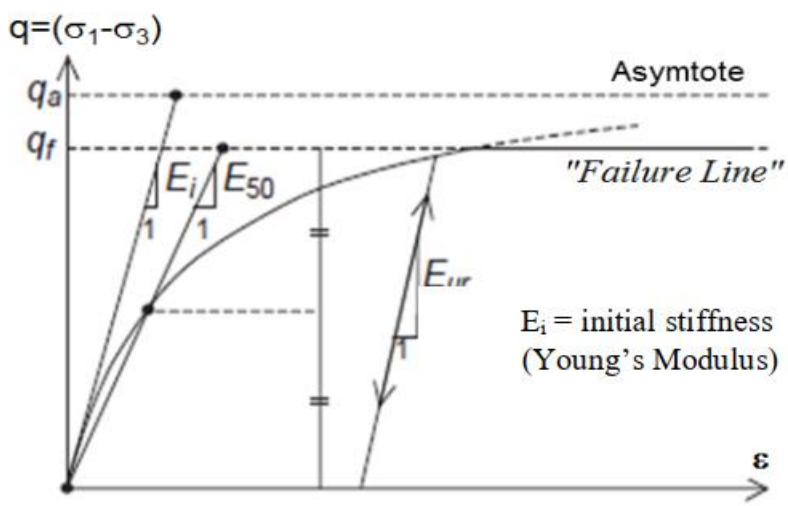


Figure 2. 10 Scheme of hardening soil model

$$E_{50} = E_{50}^{ref} \left(\frac{c' \cos\varphi' - \sigma_3' \sin\varphi'}{c' \cos\varphi' + p^{ref} \sin\varphi'} \right)^m \qquad \text{(Equation-3)}$$

$$E_{ur} = E_{ur}^{ref} \left(\frac{c' \cos\varphi' - \sigma_3' \sin\varphi'}{c' \cos\varphi' + p^{ref} \sin\varphi'} \right)^m \qquad \text{(Equation-4)}$$

In these equations, E_{50}^{ref} = reference soil modulus at confining pressure of 100 kPa, σ_3' = confining pressure, m = a constant, 1.0 for clay and silt and 0.5 for sand, c = cohesion, p^{ref} is the reference pressure, and its default value is 100 kPa, E_{ur} = unloading reloading modulus, E_{ur}^{ref} = reference unloading reloading at reference confining pressure of 100 kPa. Hardening soil model also considers the oedometer modulus E_{oed} along with loading stiffness (E_{50}) and unloading reloading modulus (E_{ur}). The oedometer modulus is calculated as below;

$$E_{oed} = E_{oed}^{ref}\left(\frac{c' \cos\varphi' - \frac{\sigma_3'}{K_0^{nc}} \sin\varphi'}{c' \cos\varphi' + p^{ref} \sin\varphi'}\right)^m \qquad \text{(Equation-5)}$$

In Equation 5, E_{oed} = Oedometer modulus, K_o^{nc} = coefficient of earth pressure at rest while the other parameters are defined above.

Chapter 3

3. METHODOLOGY & RESEARCH WORK

3.1 Introduction

This chapter reports the specifications for the materials used and methods employed for the numerical simulation to do a detailed investigation of a single and two shelves supported retailing walls for inclined silty clay backfills. It explicitly reports the methods and specifications to generate various geometrical models. The three conditions were tested for specifications of relief shelves, such as single relief shelf with location factor 0.4, width factor 0.2 and thickness 0.5 m was used, and two relief shelves with location factors 0.3 and 0.6, width factor 0.15, and thickness 0.5 m and two relief shelves with location factors 0.3 and 0.6, width factor 0.20, and thickness 0.5 m for several combinations of inclined backfills.

3.2 Geometrical configuration of model

The geometrical model including backfill, foundation and retaining wall requires to generate soil bodies and structural elements, such as beams and walls along with some other boundary conditions. The model simulates the soil bodies in the form of clusters or closed polygons and structural elements using plate elements. Table 3.1 represents the dimensions of backfill foundation and retaining wall to develop geometrical model as suggested in **(Shehata, 2016)**, **(Chauhan & Dasaka, 2018)** and **(Reddy Ayuluri & Sidhu Ramulu, 2017)**.

Table 3. 1 Specifications for Finite Element model for the present study

Sr. No	**Dimension**	**Value**	**Unit**
1	Wall height	10	m
2	Depth of foundation	4	m
3	Wall stem thickness	0.5	m
4	Wall base slab thickness	0.7	m
5	Wall toe dimension	2	m
6	Wall heel dimension	2	m
7	Width to height ratio of backfill	3	-

The shelf supported retaining walls were analyzed for three conditions in the present study, i-) retaining wall with single relief shelf with location factor 0.4, width factor 0.2 and thickness 0.5m, ii-) retaining wall with two relief shelves with location factors 0.3 and 0.6, width factor 0.15 and thickness 0.5 m, and iii-) retaining wall with two relief shelves with location factor 0.3 and 0.6, width factor 0.2 and thickness 0.5 m. The parameters location factor, width factor and thickness used in the study are defined as below:

i. Location factor (L) = $\frac{Height\ from\ top\ of\ wall\ to\ relief\ shelf\ (h)}{Height\ of\ retaining\ wall\ (H)}$ (Equation-6)

ii. Width factor (w) = $\frac{Width\ of\ relief\ shelf\ (b)}{Height\ of\ retaining\ wall\ (H)}$ (Equation-7)

iii. Thickness (t)

Figure 3.1 shows a scheme of shelf supported cantilever retaining wall with inclined backfill. The width to height ratio of 3 is used in this study as suggested in **(Shehata, 2016)**, **(Chauhan & Dasaka,**

2018) and **(Reddy Ayuluri & Sidhu Ramulu, 2017)**. The interface properties are also applied to the model as the structural elements interact with each other.

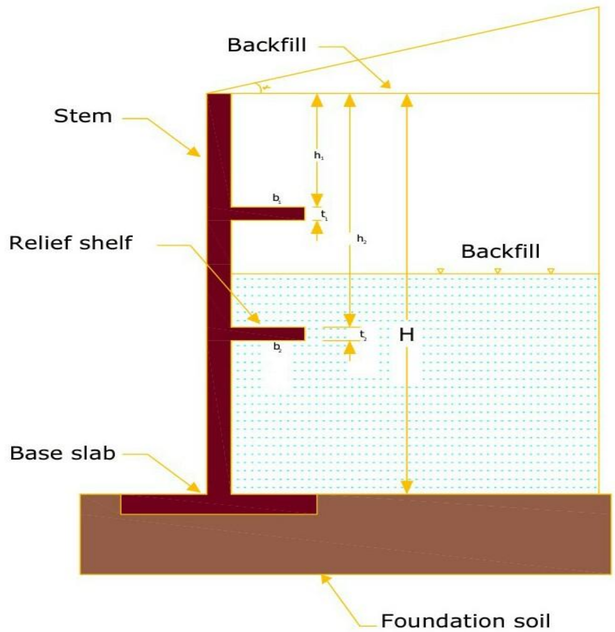


Figure 3. 1 Scheme of cantilever retaining wall with relief shelves with inclined backfill for water table at mid height

3.3 Material set properties of backfill and retaining wall

After creating the geometrical model using points, lines and plate elements, material set properties were assigned to each cluster and plate elements. The material set properties of foundation, backfill and retaining wall used in the model are specified below.

3.3.1 Backfill and foundation soils properties

The backfill and foundation soils were modelled using Mohr Coulomb's elastic perfectly plastic model to predict the behavior of relief shelves supported retaining walls. A silty clay from Sohbat Charra, district Battgram, Pakistan, was chosen for backfill, and the materials properties of this soil as published in **(Khan et al., 2016)** were used in the analysis. The properties of backfill materials are presented in Tables 3.2.

Table 3. 2 Backfill soil properties

Sr. No	**Property/parameters**	**Estimated value**	**Unit**
1	Unit weight	17.04	kN/m^3
2	Angle of internal friction	36.3	Degrees
3	Cohesion	8.1	kN/m^2
4	Dilatancy angle	0	Degrees
5	Modulus of elasticity	10000	kN/m^2
6	Poison's ratio	0.265	-
7	Interface value	0.8	-

Table 3. 3 Foundation soil properties

Sr. No	**Property/parameters**	**Estimated value**	**Unit**
1	Unit weight	19	kN/m^3
2	Angle of internal friction	35	Degrees
3	Cohesion	0	kN/m^2
4	Dilatancy angle	5	Degrees
5	Modulus of elasticity	50000	kN/m^2
6	Poison's ratio	0.3	-
7	Interface value	1	-

The interface elements were modelled using interface values varying from 0 to 1. The interface value for silty clay and sand materials was used 0.8 and 1.0, respectively. The number 1 is used for a rigid interface. Dense sand was used in the foundations and the properties as suggested in **(Shehata, 2016)** were used in the model. The properties of foundation soil are presented in Tables 3.3.

3.3.2 Retaining wall and relief shelves

Retaining walls and relief shelves were modeled using plate elements in Plaxis-2D. A linear elastic perfectly plastic model was used for modeling of structural components. The parameters including flexural rigidity (EI), axial rigidity (EA), unit weight per unit length and poison's ratio were used in the model. The parameters, i.e., EI and EA were dependent upon the elastic modulus and thickness of structural components which were estimated using Equations 8 and 9, respectively. Table 3.4 shows the properties of structural components (retaining wall and relief shelves), used in the model.

$$EA = E\,d \qquad \text{(Equation-8)}$$

$$EI = \frac{E\,d^3}{12} \qquad \text{(Equation-9)}$$

Table 3. 4 Material properties of retaining wall's stem and footing

Sr. No.	Properties	Stem	Footing	Unit
1	Modulus of elasticity	30000000	30000000	kN/m^2
2	Flexural rigidity (EI)	312500	857500	kNm/m
3	Axial rigidity (EA)	312500	857500	kN/m
4	Unit weight per length (w)	12.5	17.5	kN/m^2
5	Poison ratio (υ)	0.15	0.15	-

3.3.3 Boundary conditions

Total fixities were applied to bottom and sides to set the prescribed displacement to zero in the model. This is an important feature in Plaxis-2D to generate meshing and to do other calculations. The other boundary conditions include, i-) the analysis was carried out for backfill inclination varying from 0° to 80° with a 5^0 incremental steps, ii-) the non-yielding condition for retaining wall was used, to consider it as a rigid structure, iii-) the analysis was conducted considering water table at mid and top depth of the retaining wall.

3.3.4 Type of meshing

After creating the clusters and plate elements, and assigning properties to each cluster, i.e., retaining wall stem, footing, foundation soil and backfill soil, meshing was generated using a meshing option in the model. The type of meshing varies from very coarse to very fine, and for this study, the fine meshing criteria with 15 nodded triangular elements was followed for more accurate stress-deformation test results, instead of using 06 nodded triangular elements.

3.4 Method of analysis

Plaxis-2D utilizes different analysis methods, i.e., plastic analysis, c-ϕ analysis and dynamic analysis to simulate the soil behavior. In the present study, plastic analysis is carried out as it is used considering the soil as elasto-plastic in most of the geotechnical solutions. The backfill and foundation soils were modeled as an undrained and drained materials due to their undrained and drained behavior, respectively.

3.4.1 Calculation of control parameters

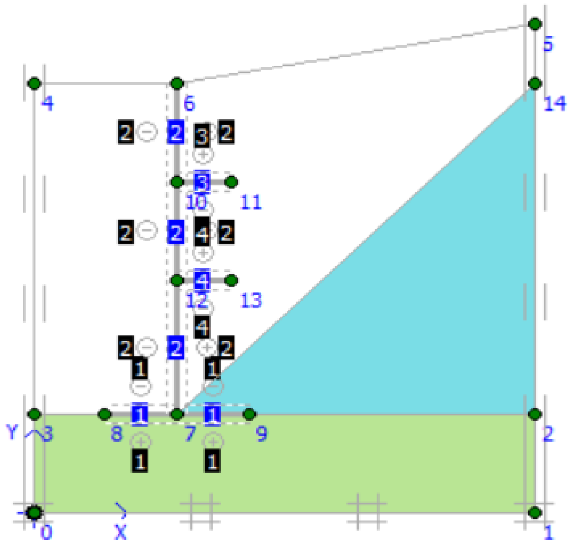
Some control parameters including reset displacement to zero and delete intermediate steps were applied to the model during calculation. In case, the displacement is not set to zero in the model, it automatically adds the displacement of previous phases in the current phase, which alternately overestimates the test data, so the displacement was set to zero in the study.

Sometimes, due to gravity loadings, unrealistic pore pressures are generated, not requisite for long term analysis. The drained analysis was conducted during gravity loadings and undrained analysis during main loading stages. Plaxis-2D has an option to delete the intermediate steps automatically, considering the important ones only. In this way, less important steps are automatically deleted. For the present study, this option was kept checked.

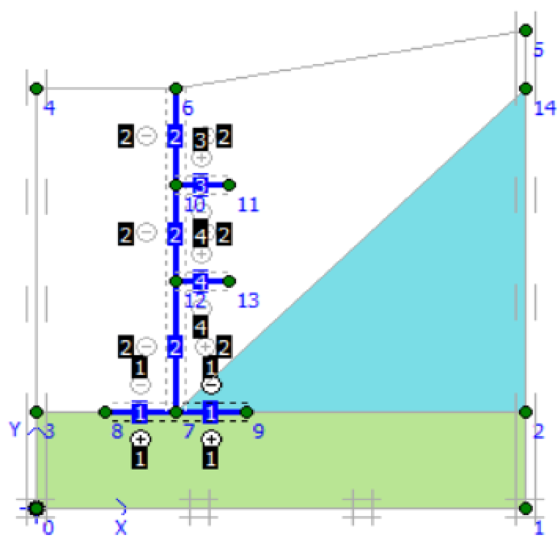
3.4.2 Loading input

The selection of loading conditions depends upon the type of problem under consideration. In the study, three types of loading inputs, such as staged construction, total multiplier, and incremental loadings were applied to simulate all the loading conditions. The staged construction involves real time analysis with different stages.

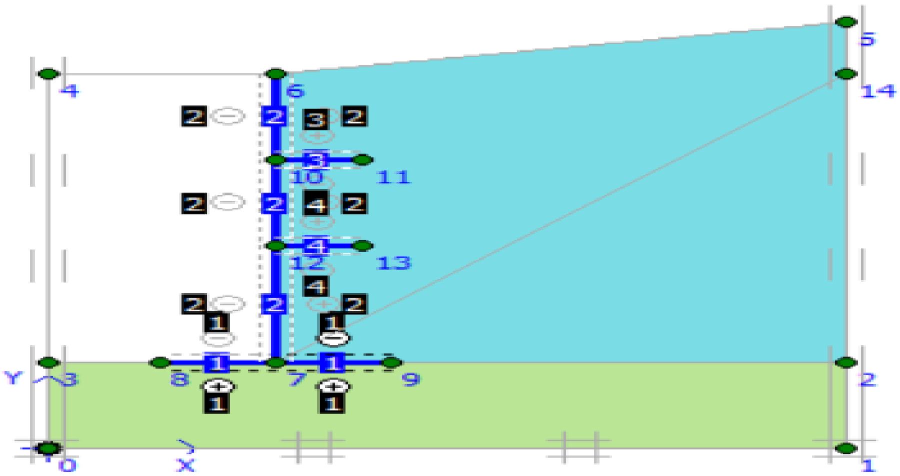
For the present study, the analysis was done in three stages as: i-) excavation of soil at 45° considering the angle of repose of soil, deactivating the cluster in the backfill (Figure 3.2a), ii-) construction of structural elements, such as retaining wall and relief shelves activating the plate elements (Figure 3.2b), and iii-) backfilling the excavated materials, activating the deactivated cluster (Figure 3.2c).



(a)



(b)

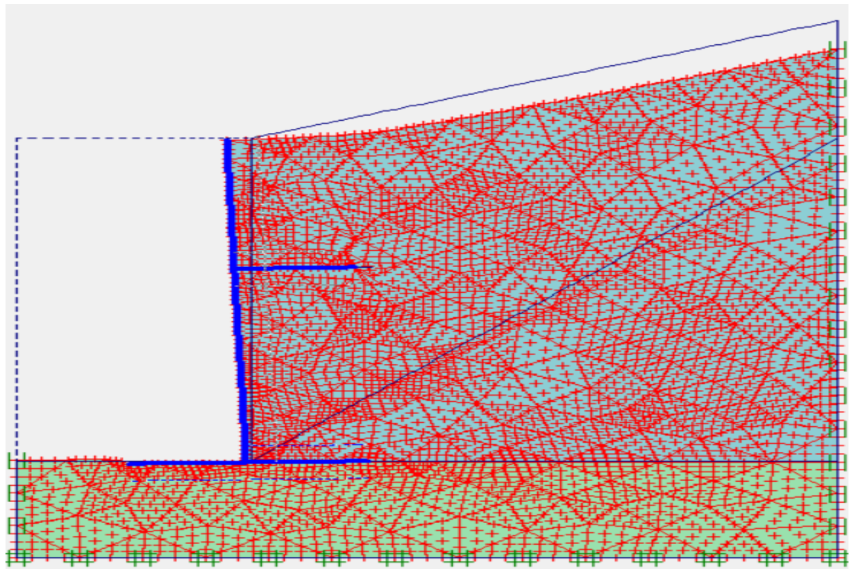


(c)

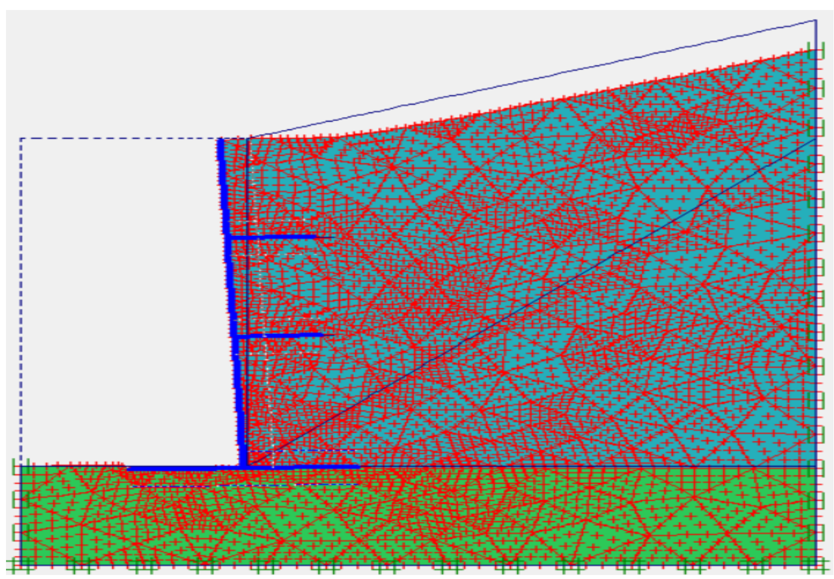
Figure 3. 2 Staged construction of the analysis (a) excavation of soil (b) construction of structural components (c) backfilling of excavated material at an angle of repose

3.5 Output and results analysis

From the output stage, the test results of parameters, such as displacements, velocities, strains, acceleration, stresses, pore water pressure and ground water etc. were obtained and analyzed. Figure 3.3 shows the deformed shapes of the model for three different conditions. A scale factor of 20 was used in the analysis means that 20 m dimension is replaced with 1m in the model



(a)



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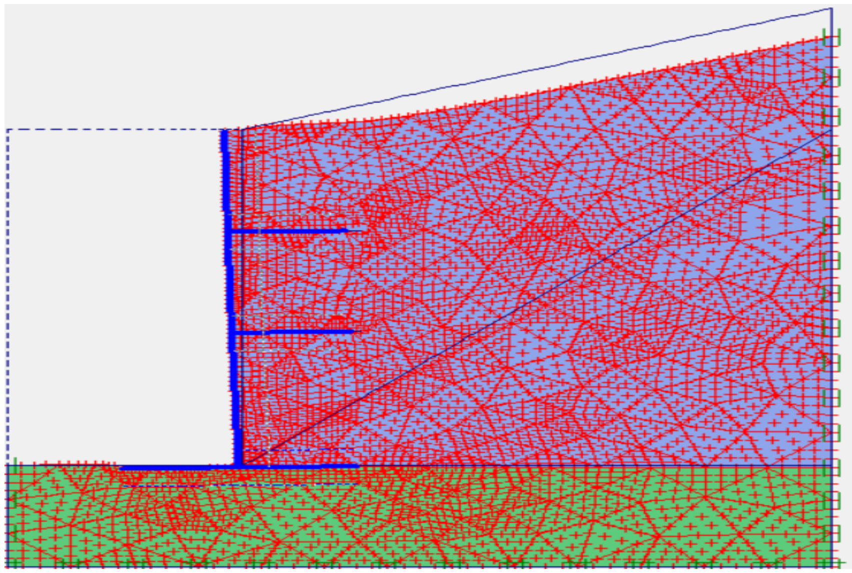

(c)

Figure 3. 3 Analysis outputs/deformed shapes of cantilever retaining wall, a) a single relief shelf (b) two relief shelves of width factor 0.15 (c) two relief shelves of width factor 0.20.

Table 3. 5 Analysis outcomes

Sr. No.	Results	Symbol	Units
1	Wall top movement	Dt	m
2	Base sliding	Ds	m
3	Shear stress	S	kN/m2
4	Bending moment	M	KNm
5	Factor of safety against overturning	FOS_O	-
6	Factor of safety against sliding	FOS_S	-
7	Factor of safety against bearing capacity	FOS_{BC}	-

3.6 Analysis scheme for numerical simulation

Several models of a single and two relief shelf supported retaining walls with inclined silty clay backfills were developed to examine their influences for active pressure, wall top movement (D_T), base sliding (D_S), shear stress (S) and bending moment (M). The factors of safety against overturning (FOS_{OT}), sliding ($FOS_{Sliding}$) and bearing capacity (FOS_{BC} were estimated to test the wall safety for different assigned conditions. In this context, 116 models were developed with different combinations. Table 3.6 shows the analysis scheme for numerical simulation.

Table 3. 6 Analysis scheme of numerical simulation*

Wall type		**Location factor**	**Width factor**	**Thickness (m)**
1	Simple wall	α= 0°, 5°, 10°, 20°, 30°, 50°, 80°		
2	Retaining wall with single relief shelf	0.4	0.2	0.5
		α= 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80°		
3	Retaining wall with two relief shelves	0.3 & 0.9	0.15	0.5
		α= 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80°		
4	Retaining wall with two relief shelves	0.3 & 0.9	0.2	0.5
		α= 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 75°, 80°		

*, All the backfill inclinations are tested for mid and top depths of water level with the wall

Chapter 4

RESULTS AND DISCUSSION

This chapter reports discussions on the basis of test data from numerical simulations for various relief shelves alternatives. The changes in profiles of parameters, such as wall top movement, base sliding, shear stress and bending moment are highlighted for variations in backfill inclinations with water level at mid and top depth of the wall. The factors of safety against overturning, base sliding and bearing capacity are also discussed for wide range of backfill inclinations. Finally, safe backfill inclinations are reported for single and two relief shelves with best alternative.

4.1 Retaining wall with single relief shelf

4.1.1 Variations in wall top movement

Figure 4. 1 shows that the wall top movement for levelled backfill is 0.017 m, and it increases with an increase in backfill inclination varying from 0.01974 m at 5° to a maximum value of 0.11159 m at 65°.

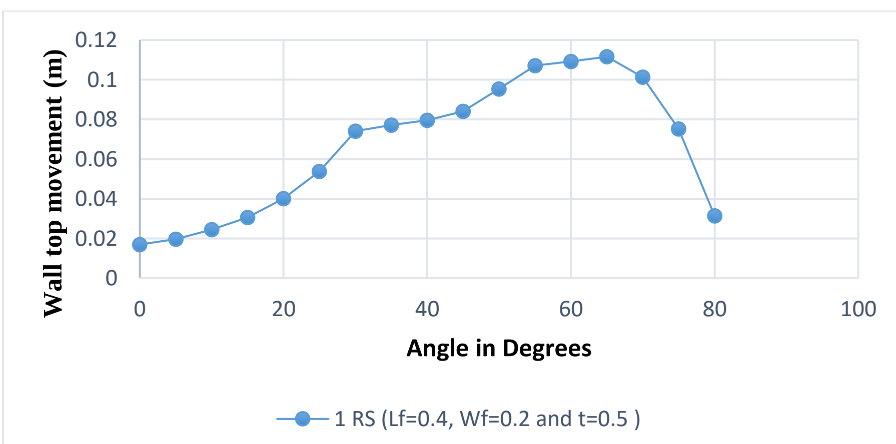

Figure 4. 1 Variations in wall top movement with changes in backfill inclinations

The wall top movement initiates to decreases for angle of inclination more than 65° with 0.03147 m at 80°.

4.1.2 Variations in base sliding

Figure 4.2 shows that the base sliding for levelled backfill is 0.00378 m, and it increases with an increase in backfill inclination up to 60°. The wall top movement initiates to decreases for angle of inclination > 60° with 0.03147 m at 80°.

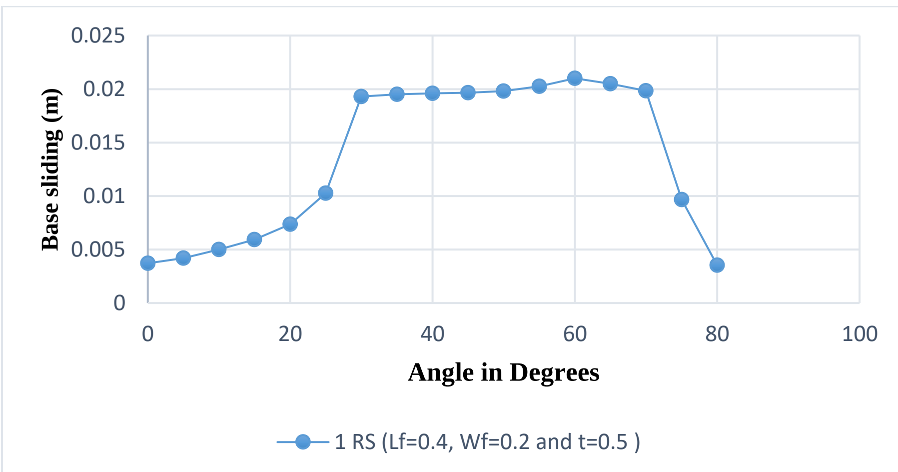

Figure 4. 2 Variations in base sliding with changes in backfill inclinations

4.1.3 Variations in shear stress

Figure 4.3 shows that the shear stress for levelled backfill is 17.11 kN/m^2, and it increases with an increase in backfill inclination up to 30°, providing a maximum value of 31.79 kN/m^2. The wall top movement initiates to decreases for angle of inclination > 30° with 13.88 kPa at 30°.

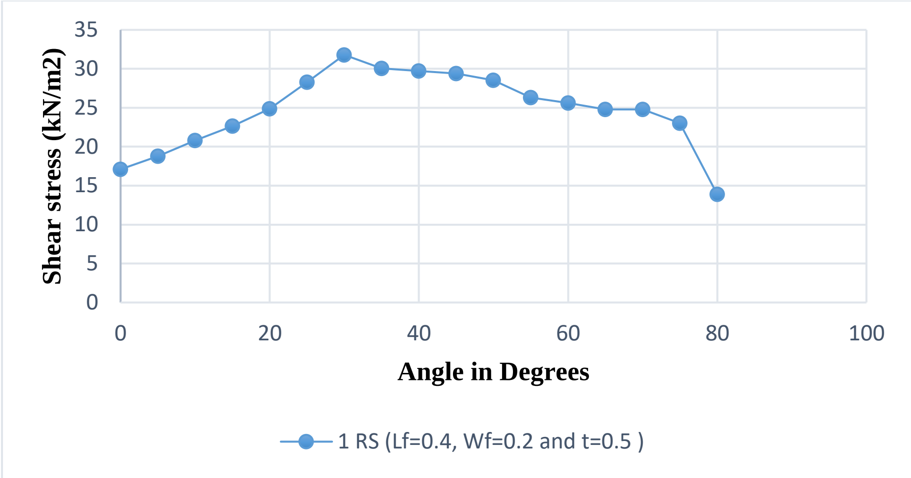

Figure 4. 3 Variations in shear stress with changes in backfill inclinations

4.1.4 Variations in bending moments

Figure 4.4 shows that the bending moments for levelled backfill is 200 kNm, and it increases with an increase in backfill inclination up to 70°, providing a maximum value of 482.53 kNm, however, the rate of increase is quite low for backfill inclination >30^0. The bending moment initiates to decreases beyond 70° inclination with 232.6 kNm at 80°.

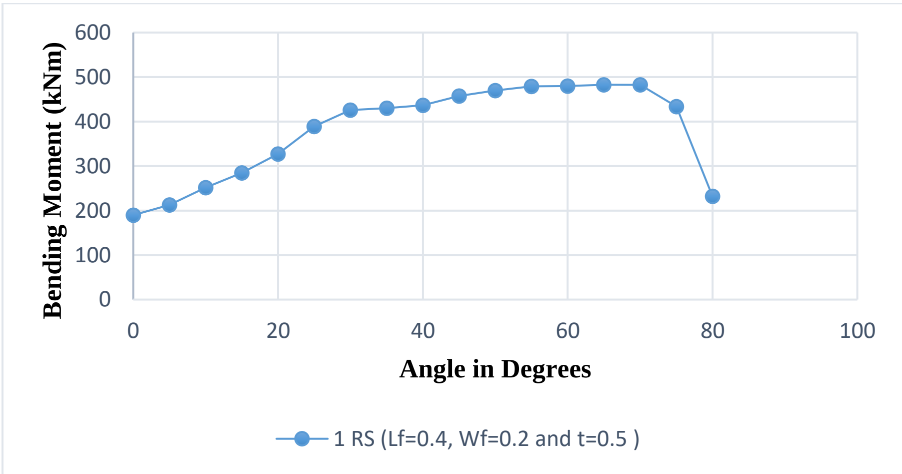

Figure 4. 4 Variations in bending moment with changes in backfill inclinations

It can be seen that the major changes in the influential parameters occur up to backfill inclination of 30^0, and after then, insignificant changes are noted.

4.2 Retaining wall with two relief shelves (width factor w = 0.15 m)

4.2.1 Variations in wall top movement

Figure 4.5 shows that the wall top moment for levelled backfill is 0.0214 m, and it increases with an increase in backfill inclination up to 65°, providing a maximum value of 0.092 m. The wall top movement initiates to decreases for angle of inclination > 65° with 0.0343 m at 80°.

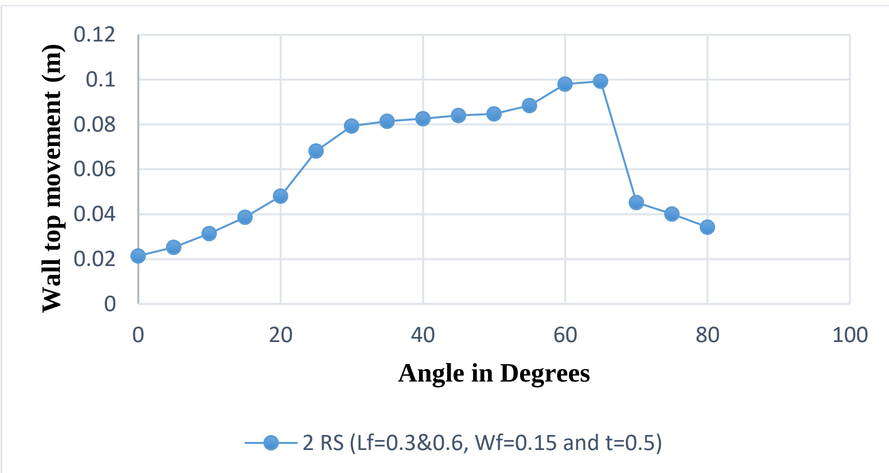

Figure 4. 5 Variations in wall top movement for cantilever retaining wall with two relief shelves (w = 0.15)

4.2.2 Variations in base sliding

The base sliding for levelled backfill is 0.003799 m as in Figure 4.6, and it increases with an increase in backfill inclination up to 40°, providing a maximum value of 0.012 m. The base sliding initiates to decreases for angle of inclination > 40° with 0.0036 m at 80°.

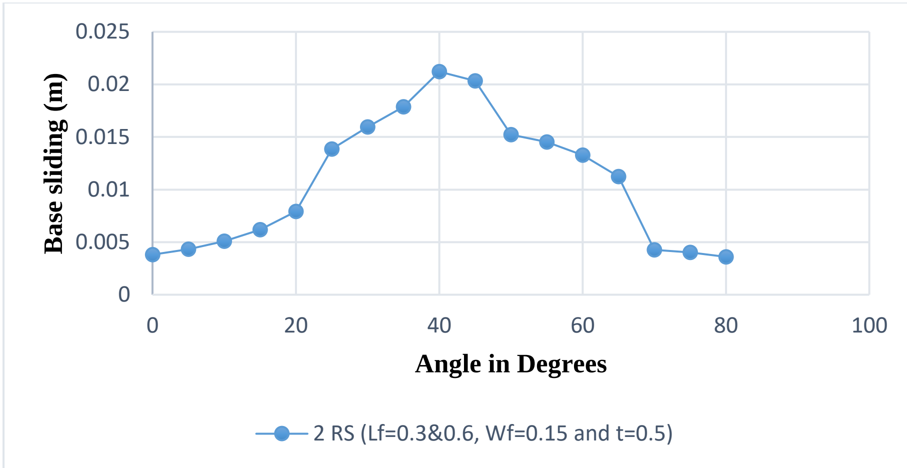

Figure 4. 6 Variations in base sliding for cantilever retaining wall with two relief shelves (w = 0.15)

4.2.3 Variations in shear stress

The shear stress for levelled backfill is 15.20 kPa as in Figure 4.7, and it increases with an increase in backfill inclination up to 30°, providing a maximum value of 29.21 kPa. The base sliding initiates to decreases for angle of inclination > 30° with 12.83 kPa at 80°, almost same as for leveled backfill.

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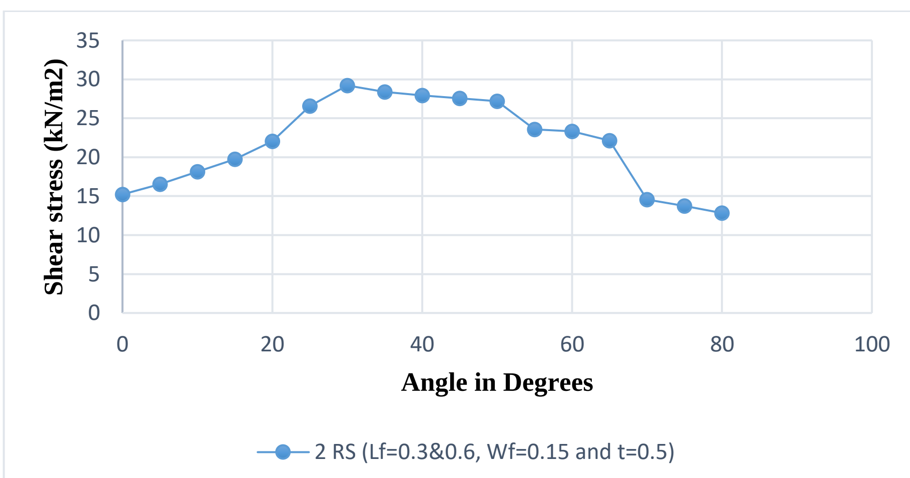

Figure 4. 7 Variations in shear stress for cantilever retaining wall with two relief shelves (w = 0.15)

4.2.4 Variations in bending moment

Figure 4.8 shows that the bending moments for levelled backfill is 193.23 kNm, and it increases with an increase in backfill inclination up to 60°, providing a maximum value of 495.83 kNm, however, the rate of increase is quite low for backfill inclination >193.23 kNm. The bending moment initiates to decreases beyond 60° inclinations with 242.4 kNm at 80°. It can be seen that the major changes in the influential parameters occur up to backfill inclination of 30^0, and after then, insignificant changes are noted.

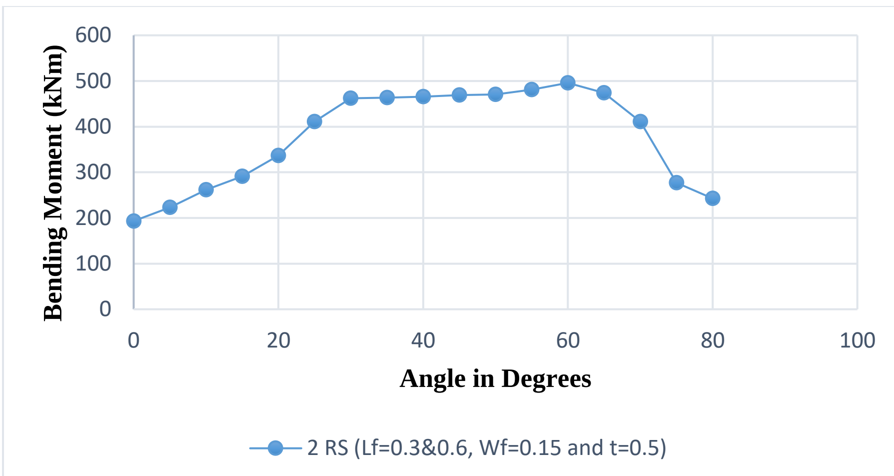

Figure 4. 8 Variation in bending moment for cantilever retaining wall with two relief shelves (w = 0.15)

The test results show that the wall top movement, base sliding, maximum shear stress, and bending moment increases with an increase in the backfill inclination up to a certain angle of inclination, but after a certain angle, they initiated to decrease due to the collapse of soil body because of higher angle of inclination. The test data also shows that for same backfill inclination, the retaining wall with a single relief shelf seems to provide better test results than two relief shelves, so the study is further carried out increasing the widths of relief shelves from 0.15 to 0.20, i.e., w = 0.20.

4.3 Retaining wall with two reliefs shelves (width factor, w = 0.20)

4.3.1 Variations in wall top movement

Figure 4.9 shows that the wall top moment for levelled backfill is 0.006126 m, and it increases with an increase in backfill inclination up to 65°, providing a maximum value of 0.100 m.

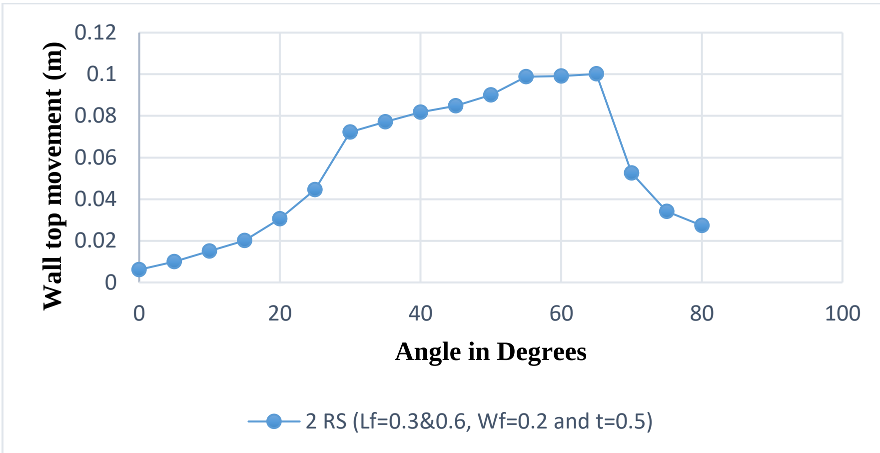

Figure 4. 9 Variations in wall top movement for cantilever retaining wall with two relief shelves (w = 0.20)

4.3.2 Variations in base sliding

The base sliding for levelled backfill is 0.003724 m as in Figure 4.10, and it increases with an increase in backfill inclination up to 60°, providing a maximum value of 0.0195 m. The base sliding initiates to decreases for angle of inclination > 60° with 0.003649 m at 80°.

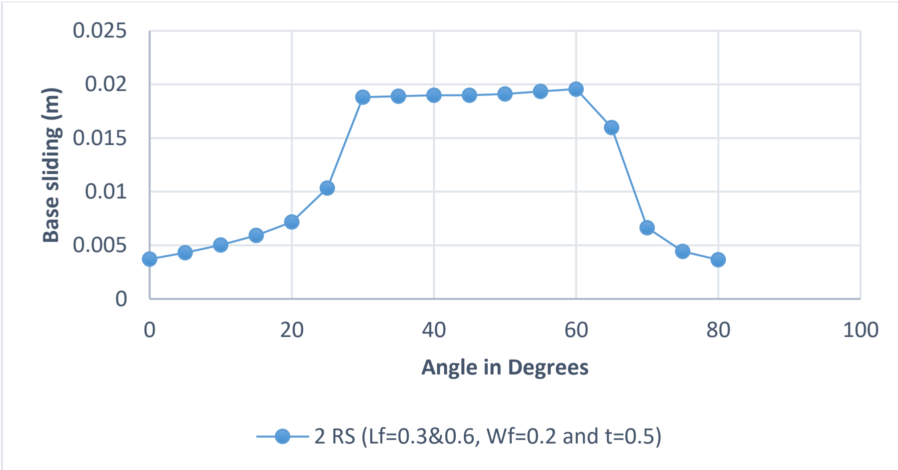

Figure 4. 10 Variations in base sliding for cantilever retaining wall with two relief shelves (w = 0.20)

4.3.3 Variation in shear stress

The shear stress for levelled backfill is 14.91 kPa as in Figure 3.11, and it increases with an increase in backfill inclination up to 30°, providing a maximum value of 28.027 kPa. The base sliding initiates to decreases for angle of inclination > 30° with 12.35 kPa at 80°.

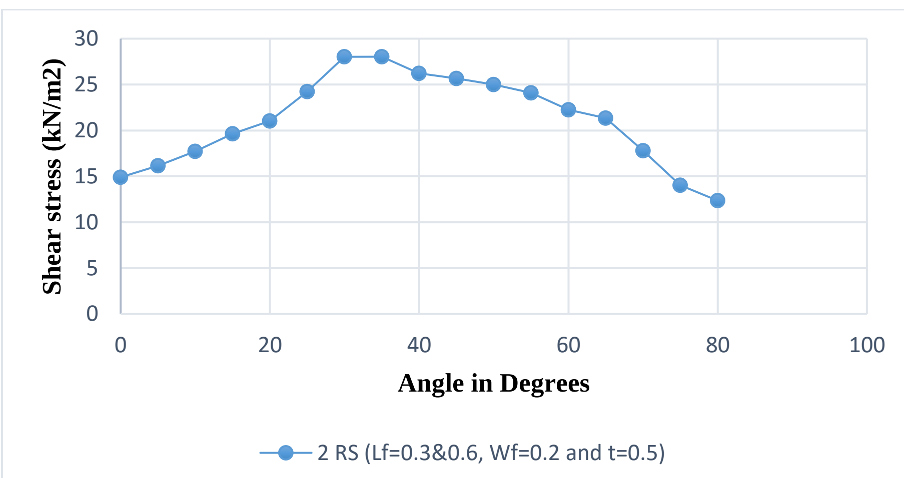

Figure 4. 11 Variations in shear stress of cantilever retaining wall with two relief shelves (w=0.2)

4.3.4 Variations in bending moment

Figure 4.12 shows that the bending moments for levelled backfill is 189.8 kNm, and it increases with an increase in backfill inclination up to 60°, providing a maximum value of 482.53 kNm, however, the rate of increase is quite low for backfill inclination > 30^0. The bending moment initiates to decreases beyond 60° inclinations with 232.6 kNm at 80°. It is observed that the major changes in the influential parameters occur up to backfill inclination of 30^0, and after then, insignificant changes are noted.

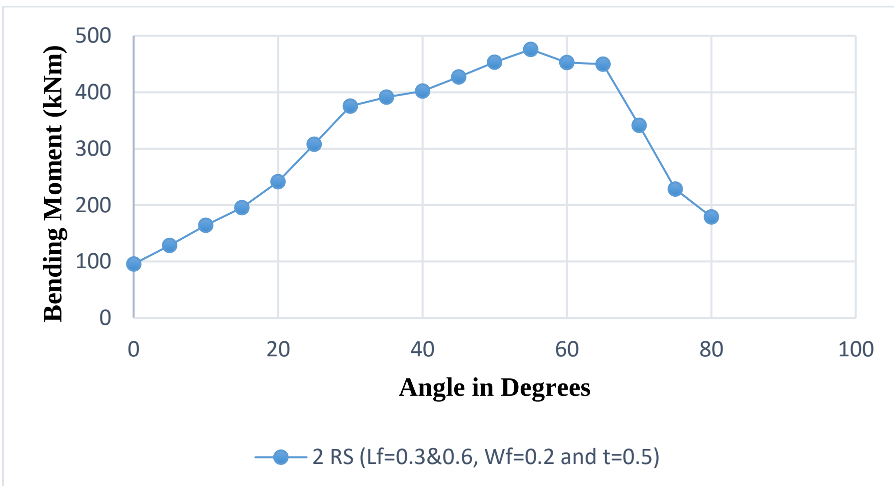

Figure 4. 12 Variations in bending moment of cantilever retaining wall with two relief shelves (w = 0.20)

4.4 Variations in factor of safeties against overturning, sliding and bearing capacity

4.4.1 Single relief shelf

As in Figures 4.13, 4.14 and 4.15 the factors of safety against overturning, sliding and bearing capacity gradually decrease with an increase in backfill inclinations of single relief shelf, and in sliding and overturning, the data points almost overlap to each other for both mid and top height of the water table, however, few differences are noted in the bearing capacity profiles, which provides safe FOS up to 20^o for top height and 25^o for mid height of the water table. For overturning and sliding, the factors of safety are noted safe for backfill inclinations of 15^o and 20^o for mid and top height of the water table. The safe factors of safety for overturning, sliding and bearing capacity are 2.06, 1.51 and 3.05 for angle of inclination of 15^o for water table at top height of wall. For water table at mid height of retaining wall, the factors of safety against overturning, sliding and bearing capacity are 3.01, 1.51 and 3.02 respectively, similar to that of **(Likitlersuang et al., 2013).** The test data shows that the water level at mid height provides relatively higher factors of safety against overturning, sliding and bearing capacity due to decrease in lateral thrust.

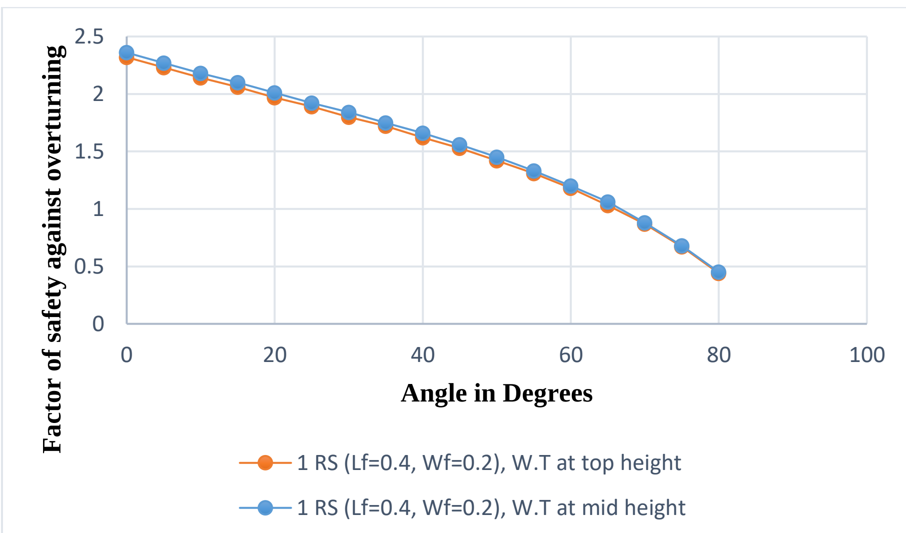

Figure 4. 13 Variations in factors of safety against overturning for water table at mid and top depths of the wall

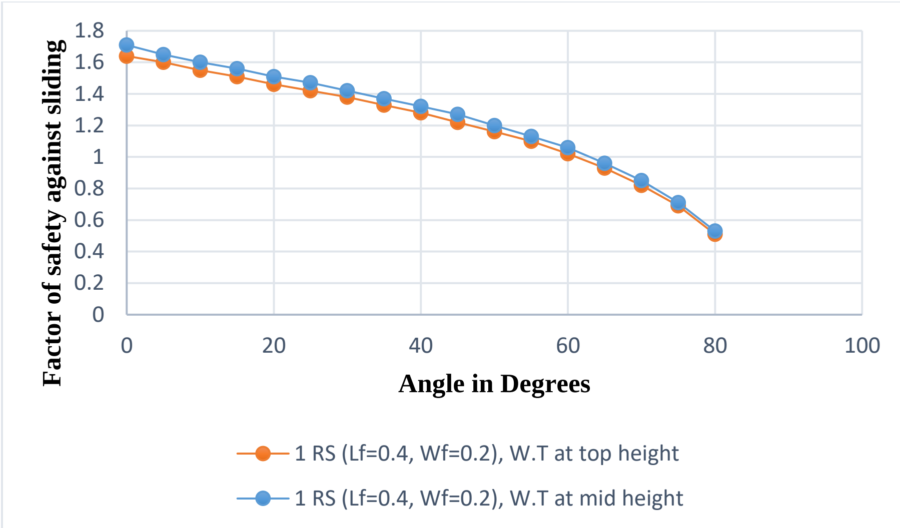

Figure 4. 14 Variations in factors of safety against sliding for water table at mid and top depths of the wall

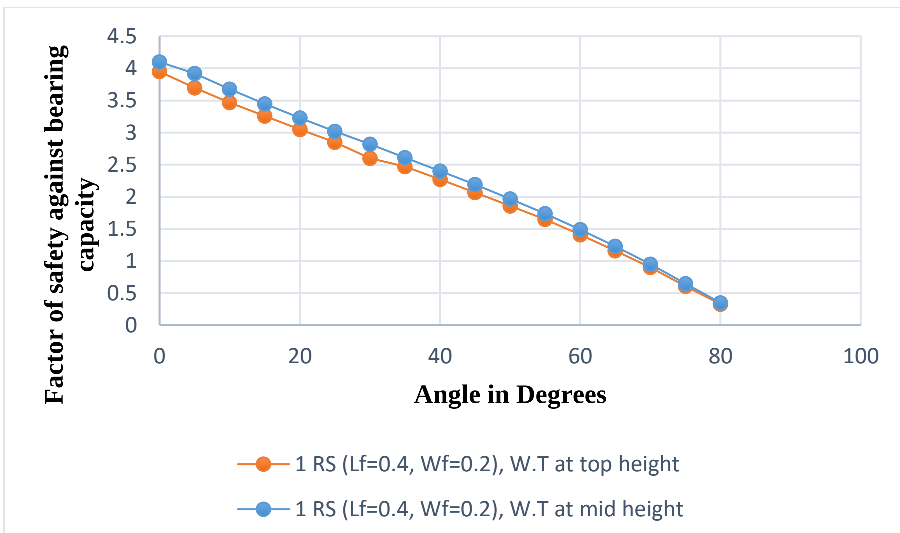

Figure 4. 15 Variations in factor of safety against bearing capacity for water table at mid and top depths of the wall

4.4.2 Two relief shelves (w = 0.15)

Similar to that of single relief shelf, the cantilever retaining wall with two relief shelves (L_f = 0.3 & 0.6, W_f =0.15 and t = 0.5 m), the factor of safety against overturning, sliding and bearing capacity decreases gradually with an increase in backfill inclination for both water levels at its mid and top height. Generally, the factors of safety; against overturning varies from 2.27 at 5° to 0.44 at

80° and from 2.32 at 5° to 0.45 at 80°, against sliding varies from 1.61 at 5° to 0.52 for 80° and from 1.67 at 5° to 0.53 at 80°, and against bearing capacity varies from 3.73 at 5° to 0.33 for 80° and 3.96 at 5° to 0.35 at 80° backfill inclinations for mid and wall height of water levels, respectively (Figures 4.24 – 4.26) As in Figures 4.16 – 4.18, the data points are overlapping to each other, showing minimal differences in FOS for two water levels. Resultantly, the FOS against overturning, sliding and bearing capacity is noted safe up to 20^{o}, 20^{o}, and 27^{o} backfill inclinations.

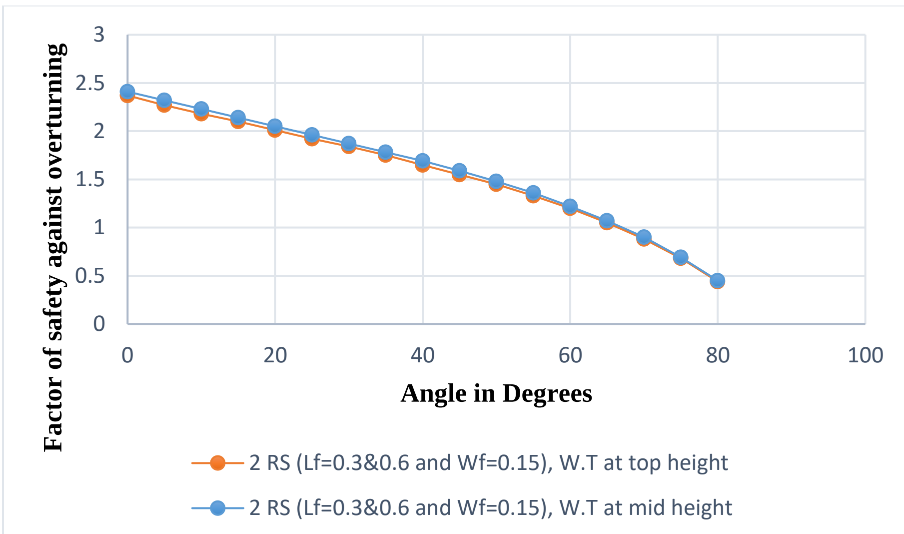

Figure 4. 16 Variations in factor of safety against overturning for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.15)

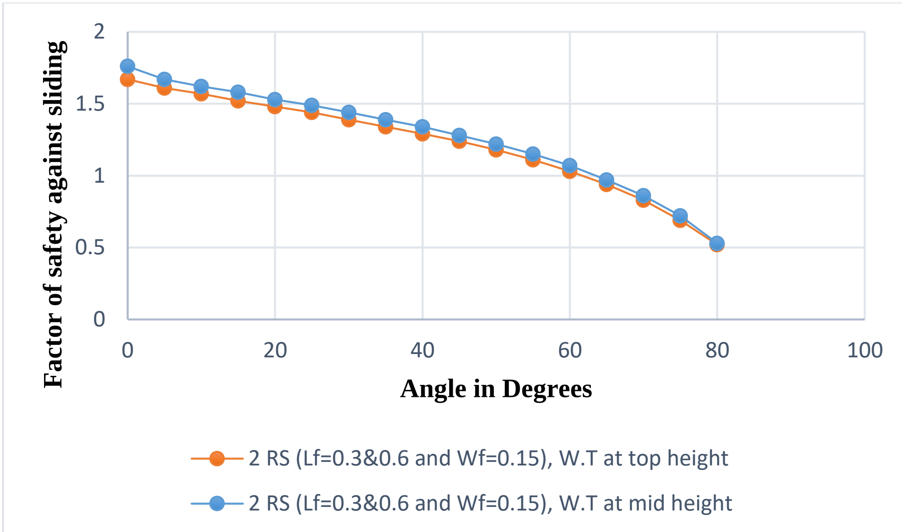

Figure 4. 17 Variations in factor of safety against sliding for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.15)

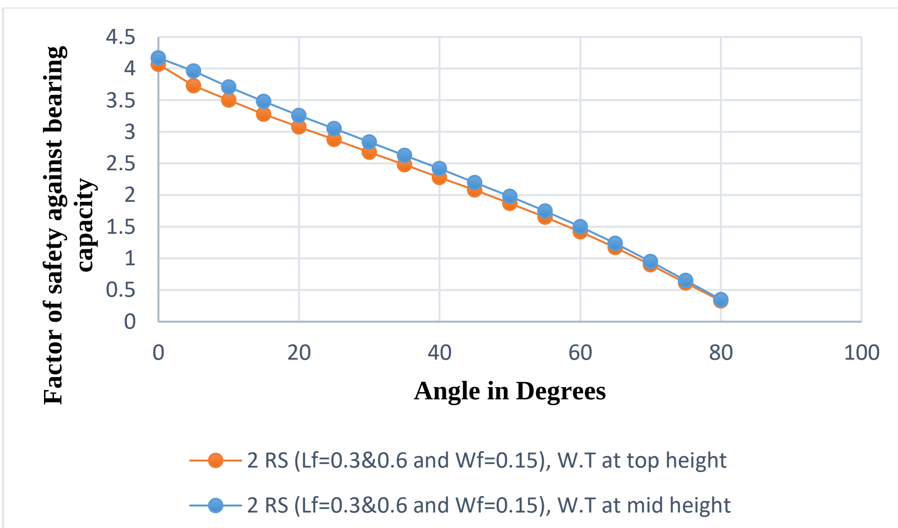

Figure 4. 18 Variations in factor of safety against bearing capacity for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.15)

4.4.3 Two relief shelves (w = 0.2)

Similar to that of single relief shelf and two relief shelves (w = 0.15), two relief shelves with w = 0.20, the factor of safety against overturning, sliding and bearing capacity decreases gradually with an increase in backfill inclination for both water levels at its mid and top height. Generally, the factor of safety; against overturning varies from 2.32 at 5° to 0.45 at 80° and from 2.36 at 5° to 0.46 at 80°, against sliding varies from 1.63 at 5° to 0.52 for 80° and from 1.69 at 5° to 0.54 at 80°, and against bearing capacity varies from 3.77 at 5° to 0.33 for 80° and 4 at 5° to 0.35 at 80° backfill inclinations for mid and wall height of water levels, respectively (Figures 4.19 – 4.21) As in Figures 4.19 – 4.21, the data points are overlapping to each other, showing minimal differences in FOS for two water levels.

Resultantly, the FOS against overturning, sliding and bearing capacity is noted safe up to 20°, 20°, and 20° for top water level and 25°, 25°, and 27° for mid water level. Resultantly, the test results as in Figures 4.13 – 4.21 show that all the situations examined for single shelf, two shelves (w = 0.15) and two shelves (w = 0.20) provide quite competitive test data, however, the factor of safety of two shelves (w = 0.20) is relatively safe for higher backfill inclinations than others.

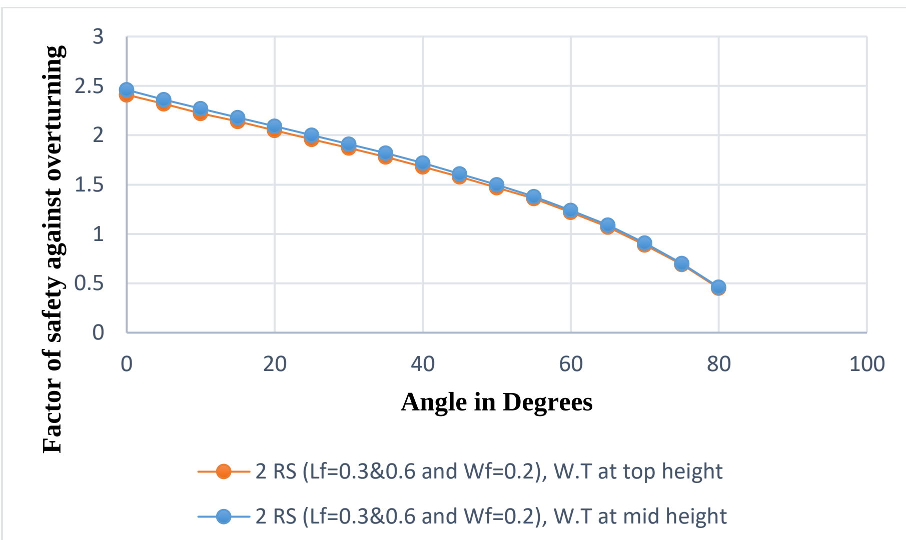

Figure 4. 19 Variations in factor of safety against overturning for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.20)

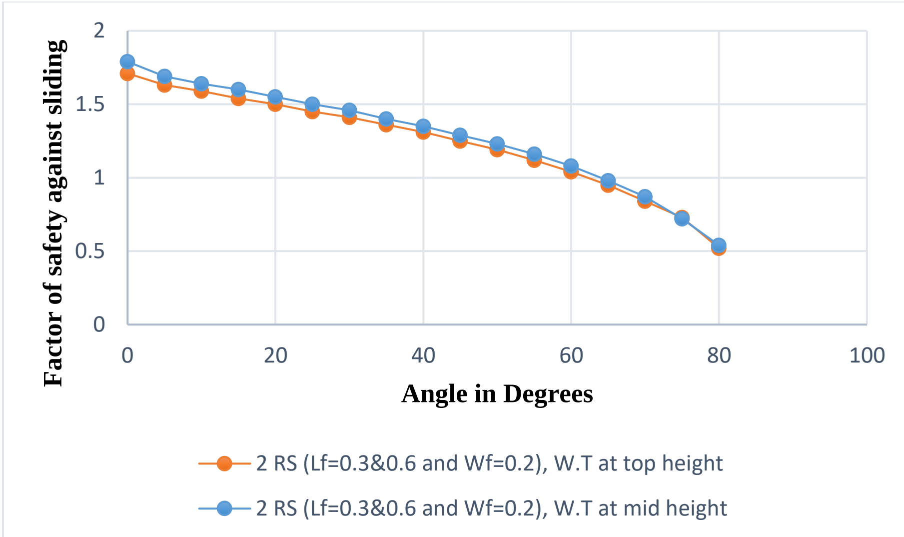

Figure 4. 20 Variations in factor of safety against sliding for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.20)

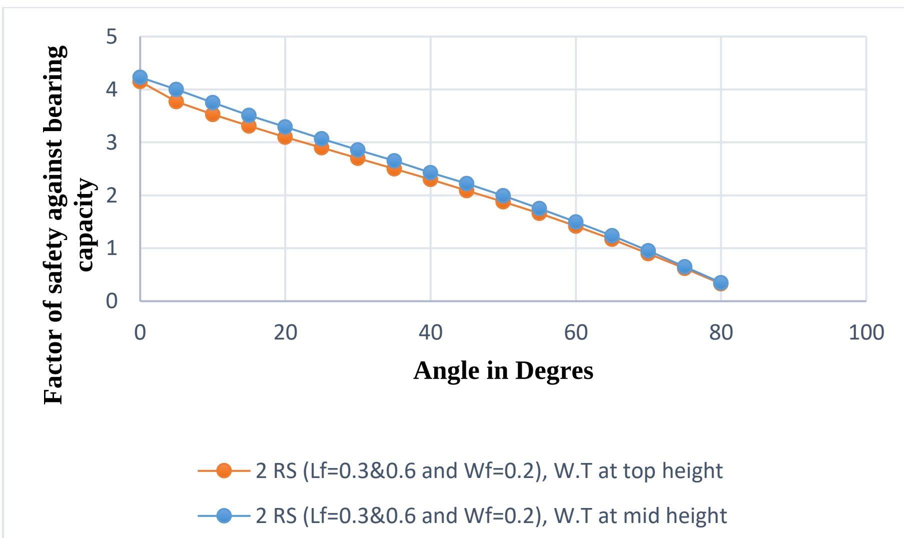

Figure 4. 21 Variations in factor of safety against bearing capacity for two relief shelves supported retaining wall with water level at mid and top depths of wall (w = 0.20)

4.5 Comparative evaluation of parameters influencing the wall stability

Figure 4.22 – 4.25 show that the influential parameters, i.e., wall top movement, base sliding, shear stress and bending moment increase with an increase in backfill inclinations initially, and the

rate of increase is relatively high for backfill inclinations up to 30°, but beyond this point, they show less increase up to 60°, and after then provide a sharp drop for all alternatives. However, it can be seen form Figures 4.22 – 4.25 that the nature of all profiles is consistent for changes in backfill inclinations, except that the base sliding profile two shelves with width factor, 0.20 is quite different to others.

Resultantly, two shelves with width factor, 0.2 relatively provides lower peak for all backfill inclinations than other alternatives for all influential parameters, due to which the factors of safety of this alternative are safe towards higher inclinations as in Figures 4.13 – 4.21.

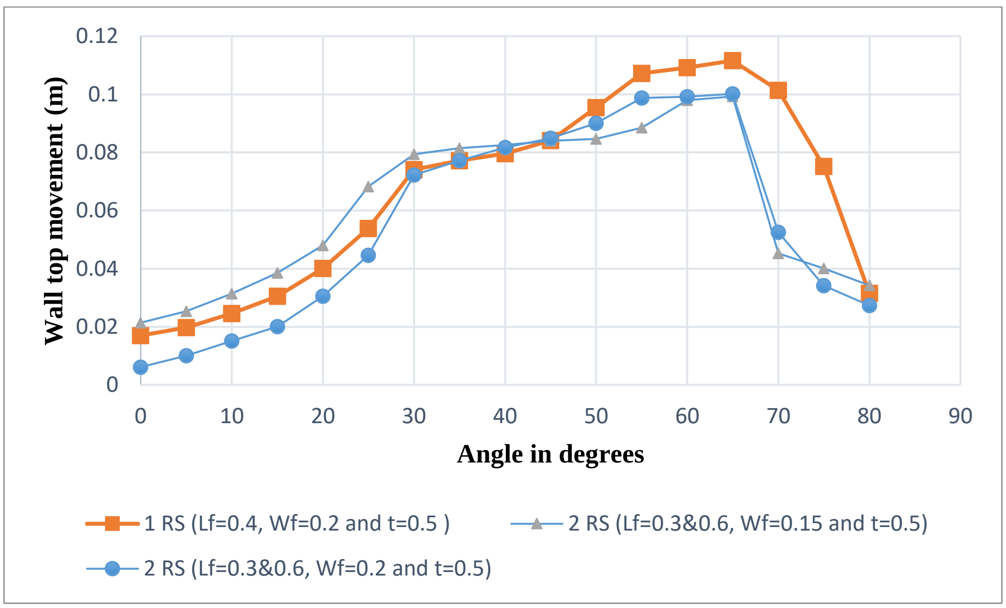

Figure 4. 22 Variations in wall top movement for backfill inclinations

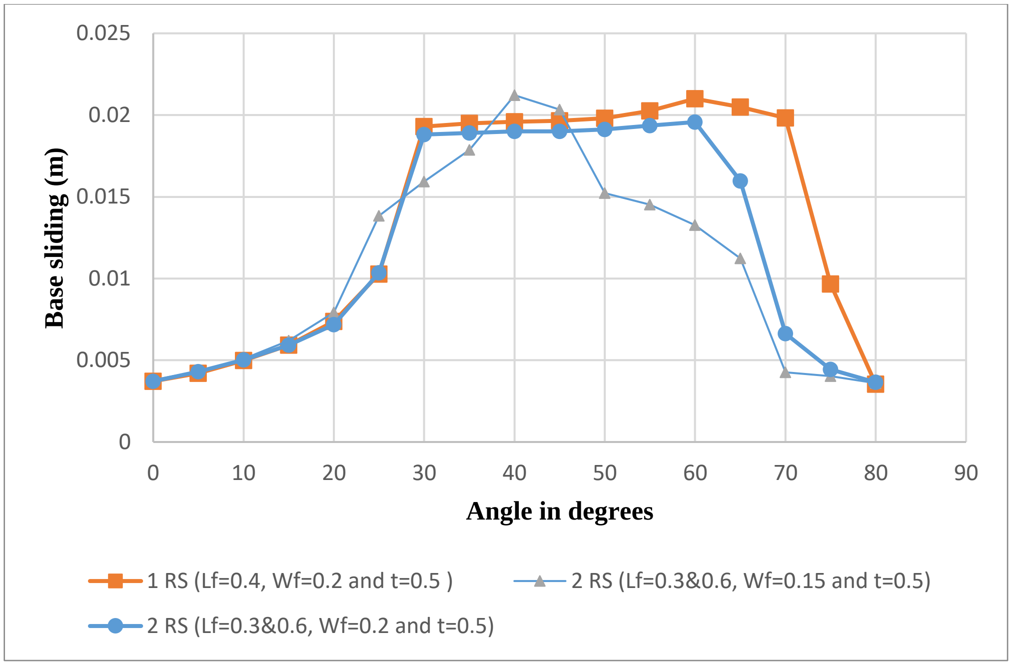

Figure 4. 23 Variations in base sliding for backfill inclinations

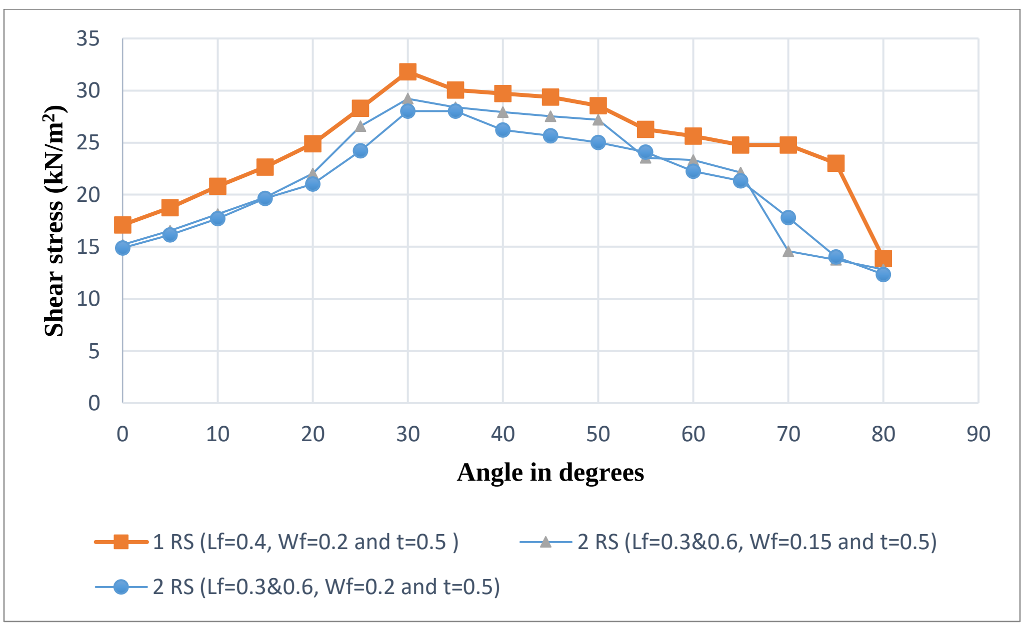

Figure 4. 24 Variations in shear stress for backfill inclinations

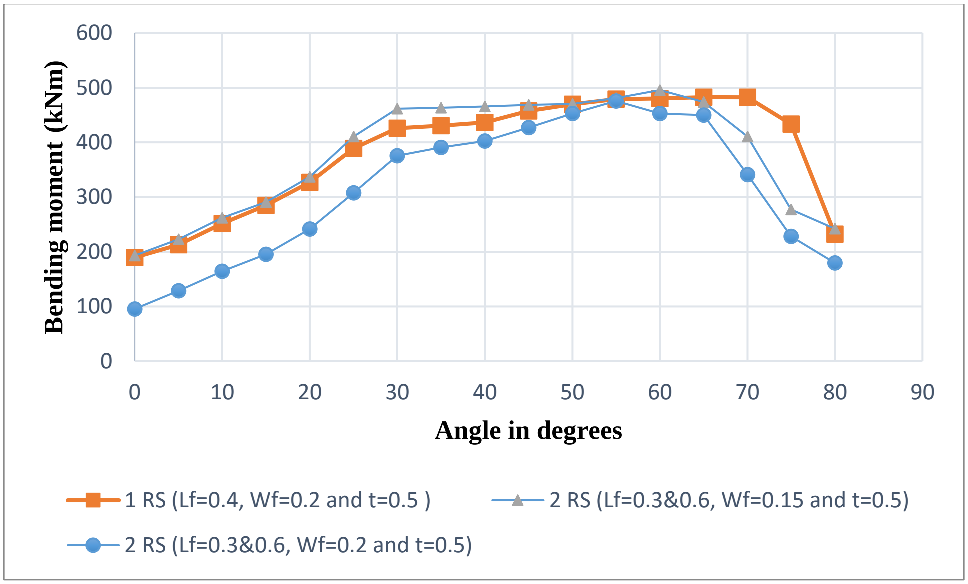

Figure 4. 25 Variations in bending moment for backfill inclinations

4.6 Comparative evaluation of factors of safety for backfill inclinations

Figures 4.26 shows that all factors of safety against overturning provides less differences at particular inclinations for all alternatives, and as well as for mid and top height of the water level, and similarly as in Figures 4.27 - 4.28, the factors of safety against base sliding and bearing capacity also provide fewer differences and data points appear overlapping to each other. Furthermore, the data points are merging into each other with an increase in backfill inclinations with minimal differences beyond backfill inclination of 50° and alternately shows rapid decrease in factors of safety which is due to the fact that the higher inclined load provides larger thrust, which alternately results reduces the FOS. Furthermore, as in Figures 4.22 to 4.25, the wall top movement, base sliding, shear stress and bending moment are almost equal at backfill inclination of 80° and at levelled surface but the factors of safety (Figures 4.26 – 4.28) are relatively too low at 80°. which is again due to maximum thrust because of higher backfill inclinations.

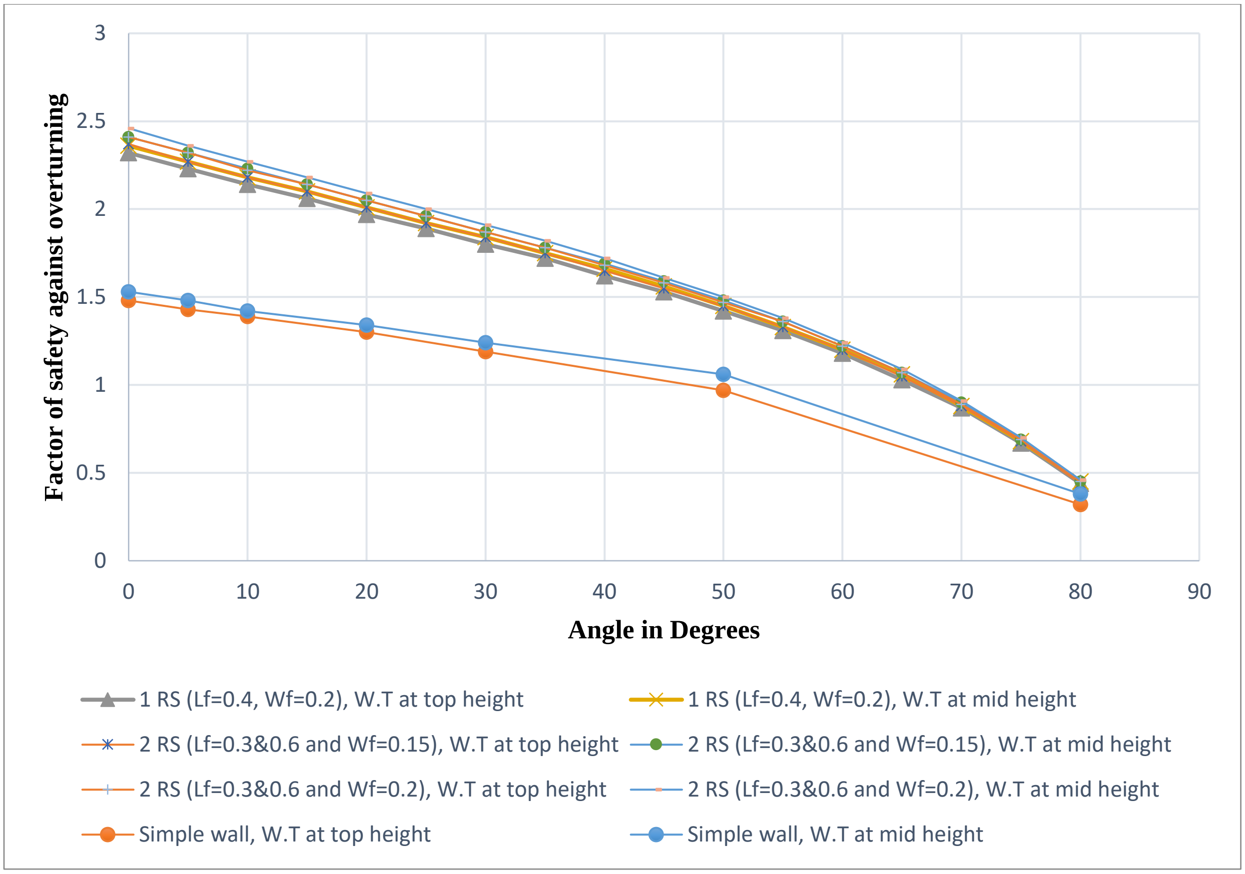

Figure 4. 26 Comparative analysis of factor of safety against overturning for backfill inclinations

Table 4.1 shows the factors of safety for maximum backfill inclinations to support the wall without failure, and it is clear that the backfill inclinations from 15 to 20 degrees is safe to support the wall without failure and the wall is relatively stable at higher backfill inclinations for two shelves with w = 0.20 than other alternatives, and the alternatives are unable to provide major differences in backfill inclinations against safe factors of safety for practical consideration.

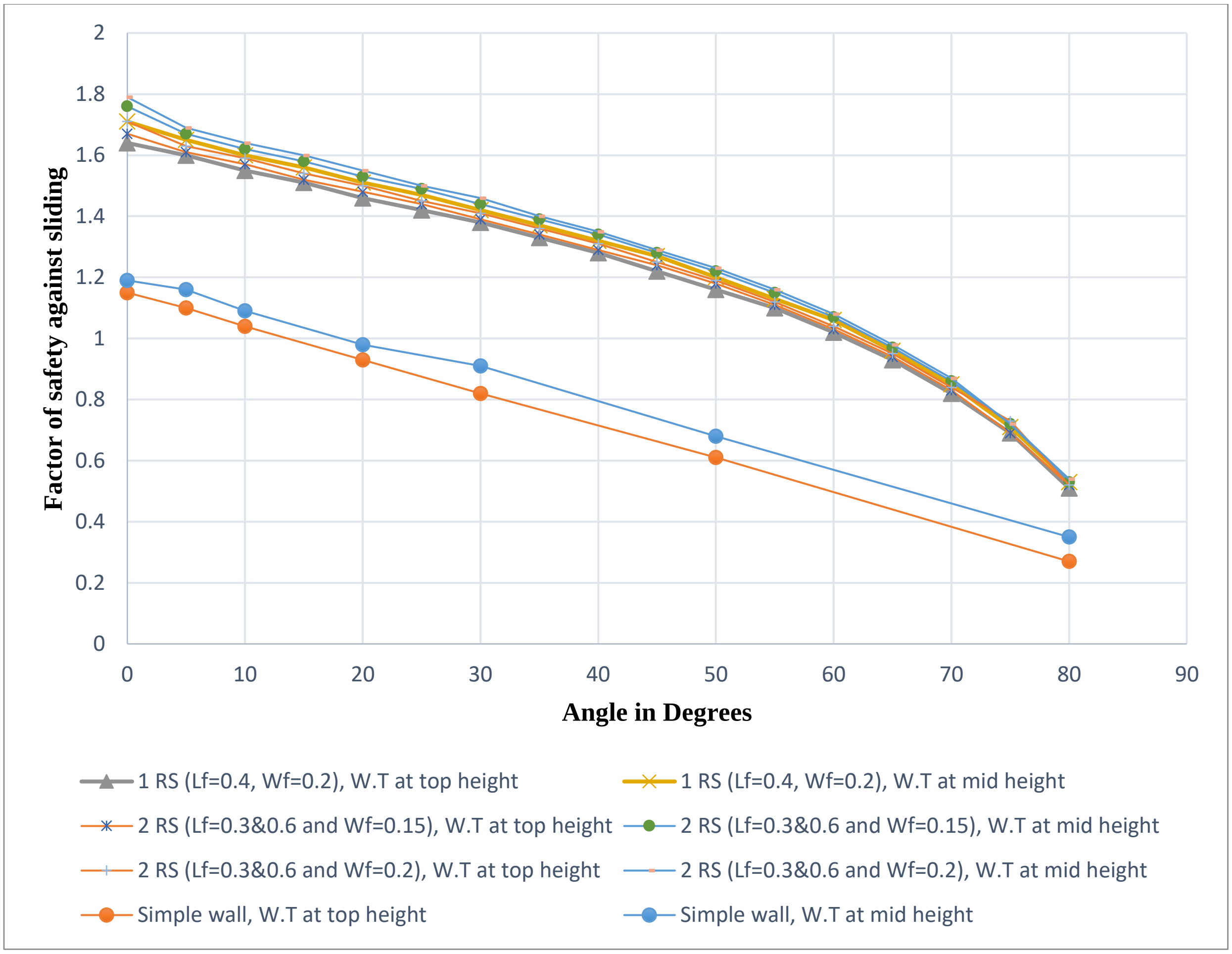

Figure 4. 27 Comparative analysis of factor of safety against sliding for backfill inclinations

Furthermore, the test data as in Tables 4.1 and 4.2 show that the simple retaining wall relatively provides quite lower factors of safety than relief shelve supported retaining walls. For backfill inclination of 20°, a simple wall provides FOS against overturning and sliding of 1.3 and 0.93 to that that of 2.01 and 1.52 for two relief shelves, respectively. As in Table 4.1, the simple wall is even unable to provide safe FOS against sliding and overturning for levelled backfill (0° inclination) but the relief shelves supported walls are safe up to a backfill inclinations of 20° to 25°. It can be concluded from the test data that there are significant benefits to use relief shelves to strengthen the retaining wall of silty clay backfill.

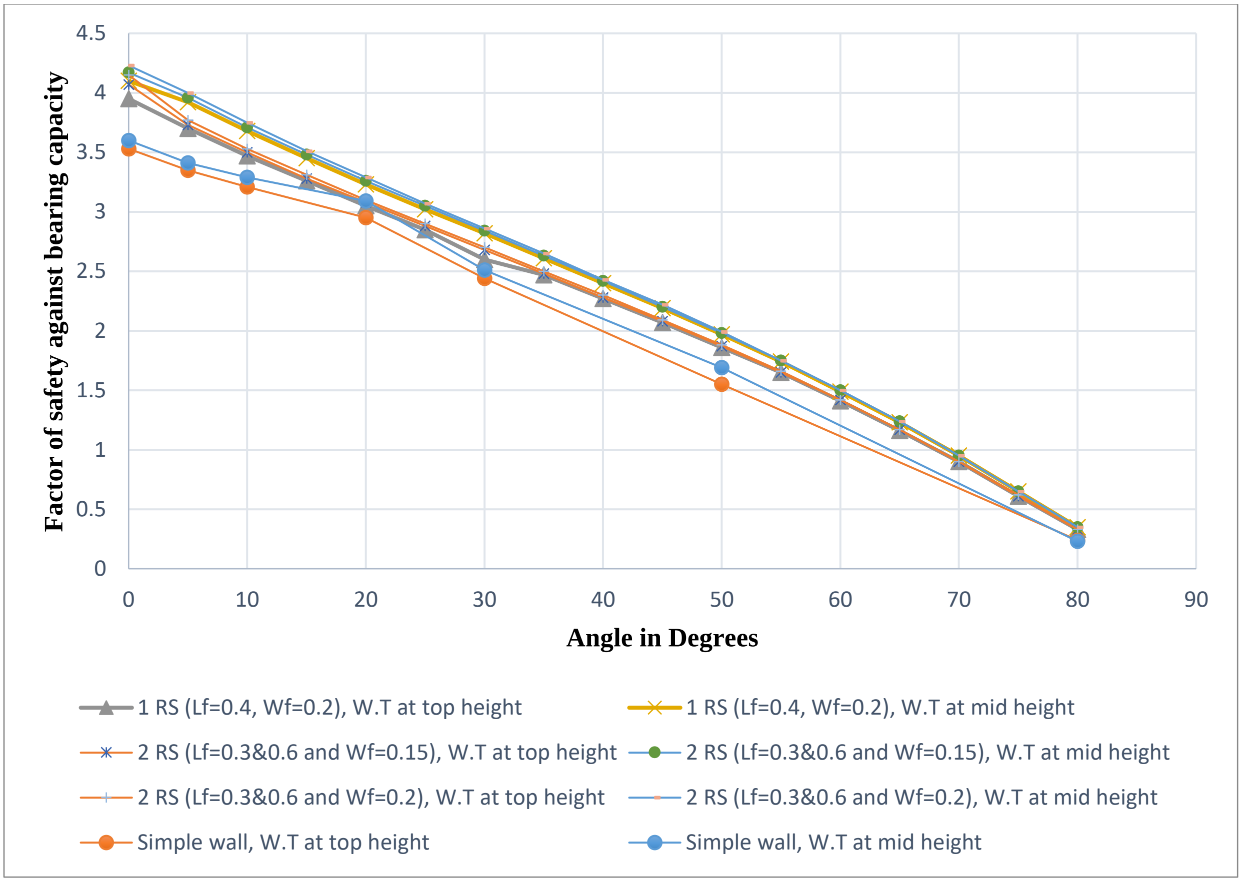

Figure 4. 28 Comparative analysis of factors of safety against bearing capacity for backfill inclinations

Table 4.1 Factor of safeties of shelf supported retaining walls

Cantilever retaining wall	Variation of factor of safety against Overturning				Variation of factor of safety against sliding				Variation of factor of safety against bearing capacity			
	Water table at top height of wall		Water table at mid height of wall		Water table at top height of wall		Water table at mid height of wall		Water table at top height of wall		Water table at mid height of wall	
	Max. angle	FOS	Max. angle	FOS	Max. angle	FOS	Max. angle	FOS	Max. angle	FOS	Max. angle	FOS
1 RS (Lf= 0.4 Wf=0.2 and t=0.5m)	15	2.06	20	2.01	15	1.51	20	1.51	20	3.05	25	3.02
2 RS (Lf=0.3&0.6, Wf=0.15 and t=0.5m)	20	2.01	20	2.05	15	1.52	20	1.53	20	3.08	25	3.05
2 RS (Lf=0.3&0.6, Wf=0.2 and t=0.5m)	20	2.05	25	2.0	20	1.5	25	1.5	20	3.1	25	3.07

Table 4.2 Factor of safeties of simple retaining wall

Cantilever retaining wall	Variations in factors of safety against overturning			Variations in factor of safety against sliding			Variations in factor of safety against bearing capacity		
	Angle of inclination in degrees	W.T at top height of wall	W.T at mid height of wall	Angle of inclination in degrees	W.T at top height of wall	W.T at mid height of wall	Angle of inclination in degrees	W.T at top height of wall	W.T at mid height of wall
		FOS	FOS		FOS	FOS		FOS	FOS
Simple wall	0	1.48	1.53	0	1.15	1.19	0	3.53	3.6
	5	1.43	1.48	5	1.1	1.16	5	3.35	3.41
	10	1.39	1.42	10	1.04	1.09	10	3.21	3.29
	20	1.3	1.34	20	0.93	0.98	20	2.95	3.09
	30	1.19	1.24	30	0.82	0.91	30	2.44	2.51
	50	0.97	1.06	50	0.61	0.68	50	1.55	1.69
	80	0.32	0.38	80	0.27	0.35	80	0.24	0.23

Chapter *5*

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

i. The wall top movement, base sliding, maximum shear stress and maximum bending moment increases with an increase in backfill inclination up to a certain level, but after this point, the influential parameters initiate to decrease.

ii. The two shelves alternative with width factor, 0.2 provides lower peaks for wall top movement, base sliding, shear stress and bending moments for all backfill inclinations and due to which it provides relatively lower factors of safety than other alternatives.

iii. For single shelf, two relief shelves with width factor 0.15, and two relief shelves with width factor 0.20, the backfill inclinations are safe up to 15, 20 and 25 degrees respectively, providing factors of safety within the permissible limits against overturning, base sliding and bearing capacity.

iv. All alternatives show higher rate of increase in wall top movement, base sliding, maximum shear stress and maximum bending moment for backfill inclinations up to 30° and furthermore, after 60°, they show a random decrease, which is due to collapse of the soil backfill wedge for higher backfill inclinations.

v. The backfill inclinations for safe factors of safety are almost 5 degrees less for water depth at wall top than at mid depth, however differences in factors of safety are not so significant for two water levels.

vi. There is no efficacy to use the backfill inclinations beyond a certain degree, as the inclinations beyond 15 ~ 20 degrees are unable to provide safe factors of safety for silty clay backfills with both water level at top and mid depths of the wall for all alternatives.

vii. The simple retaining wall relatively provides quite lower factors of safety than relief shelve supported walls and it is even unable to provide safe FOS against sliding and overturning for levelled backfill, i.e., 0° backfill inclination.

viii. It can be concluded from the test data that there are significant benefits to use relief shelves to strengthen the retaining wall of silty clay backfill.

5.2 Recommendations

- There is need to modify the scheme of retaining wall to test the safe factors of safety against higher backfill inclinations.
- Investigations can be carried out on same type of retaining wall with cohesive backfills with higher cohesion

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