INFLUENCE OF PRESSURE RELIEF SHELVES ON THE STABILITY OF RETAINING WALLS WITH COHESIVE BACKFILL

By

Abdul Qader Khan Ghori

NUST- 2017-MS-Geotech-00000205951

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)

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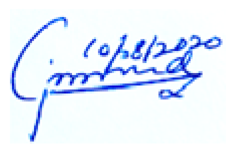

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DEDICATED

TO

MY BELOVED PARENTS

WHO GAVE ME A LOT OF SUPPORT

AND

ENCOURAGEMENT

ACKNOWLEDGEMENT

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ABSTRACT

A retaining wall is a structure, designed and constructed to resist the lateral earth pressure of soil so that the soil on both sides of it can be retained at different levels, and the examples include gravity wall, piling wall, cantilever wall, and anchored wall, etc. Numerous researches have been conducted in this field to innovate methods and to improve the strength of retaining walls on economic grounds and several theories and hypothesis have been proposed in this respect so far such as counterfort wall, buttressed wall and providing key at the base of retaining wall, etc. One of the most effective but least studied methods is to construct pressure relief shelves monolithically with the wall and extend them within the backfill materials to increase its stability. The design of retaining walls including relief shelves is quite complex as it involves several parameters such as width, location, and thickness of shelves, etc. that need to be considered for its design. Secondly, all the literature on this type of wall is associated with non-cohesive backfill. Thus, this study elaborates the influence of pressure relief shelves on the stability of retaining walls, considering all important influential parameters of relief shelves, while cohesive soil is used as a backfill material. For the purpose a parametric study by finite element analysis of this type of wall using PLAXIS 2D is executed. The study allows a discussion on the effects of the width, location, and thickness of relief shelves on the resulting lateral earth thrust, shear stresses, wall top movement, base sliding and overturning bending moment along the wall. Reduction in active earth thrust up to 16.58 and 24.34 percent, top wall movement up to 114.98 and 85.14 percent, and base sliding up to 28.57 and 31.66 percent, etc. has been obtained due to the provision of single and two shelves, respectively, with certain size and location is shown; therefore, enhancing the stability of wall. However, for high retaining walls with cohesive soil behind them and have problems with stability, the study recommends to provide relief shelf at a certain location, along with some precautions to enhance the stability.

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LIST OF SYMBOLS / ABBREVIATIONS

P_a	Active earth pressure
P_p	Passive earth pressure
S	Shear stress
M	Bending moment
P	Total lateral thrust
$\emptyset$	Angle of internal friction
c	Cohesion
D_T	Wall top movement
D_S	Base sliding
FOS	Factor of safety
LEPP	Linear elastic perfectly plastic
γ	Unit weight
ψ	Angle of dilatancy
E	Young's modulus
K_0	Coefficient of earth pressure at rest
K_p	Coefficient of passive earth pressure
K_a	Coefficient of active earth pressure
ν	Poisson's ratio
Z_0	Depth of cut off
W	Weight of failure wedge
θ	Angle of failure plane with horizontal
ρ	Angle of failure plane with horizontal (Coulomb's theory)
μ	Coefficient of shear resistance
b	Width of relief shelf
L	Location factor of relief shelf
w	Width factor of relief shelf
t	Thickness of relief shelf

q_m	Bearing capacity of foundation
T	Thickness of base slab of retaining wall
H	Height of retaining wall
ε^p	Plastic part of strain rate
λ	Plastic multiplier
EA	Axial stiffness
EI	Bending stiffness
d	Thickness of plate element in Plaxis
G	Shear modulus

Chapter. 1

1. INTRODUCTION

1.1. General

A structure constructed to withstand the pressure exerted by a mass of geomaterial retained is known as retaining wall. Soil bodies forming slopes due to cut or fill are retained by the retaining walls. The soil mass behind the retaining structure may be in its natural state or in a disturbed condition such as backfilled earth, which exerts a pressure in lateral direction exerted on the wall, known as lateral earth pressure. One of the oldest questions in the field of civil engineering is the estimation of lateral earth pressure exerted on the retaining wall, which will control its design. Lots of theoretical and experimented works have been done in this field; many theories and hypotheses have been proposed.

Retaining wall is an integral part of many construction projects including bridges, roads, dams, basements, and land use, and slope stability. The most commonly used retaining walls are gravity and gabion retaining walls which are bulky in size. Some situations require contractors to build high retaining walls, for which the massive gravity and gabion walls may not be feasible due to restrictions related to economy and space. A cantilever retaining wall might be a better choice for such conditions, where higher backfills are to be retained. As these walls are to be designed for higher earth pressures, numerous researches have been conducted in this field to innovate methods and to improve the strength of retaining walls on economic grounds and several theories and hypothesis have been proposed in this respect so far, such as counterfort (Babcock, 2018) and buttress retaining walls (Ou et al., 2008), and other modifications like soil nailing (Byrane et al., 1996), and batter piles (Seo et al., 2016), etc. But this area is still lack in research and there is significant potential to improve the stability of walls, focusing on saving the construction materials.

1.2. Retaining wall with relief shelves

This thesis is planned to carry out the stability analysis of a special type of retaining wall in which relief shelves or platforms are monolithically attached to the wall into the backfill (Figure 1.1). The provision of pressure relief shelves reinforces the backfill materials reducing the intensity of earth pressure applied on the wall, which cuts down the size of the retaining wall along with enhanced stability. They are suitable for the cases where lofty retaining walls are required to be constructed and the economy is one of the major factors to be considered before constructing retaining walls.

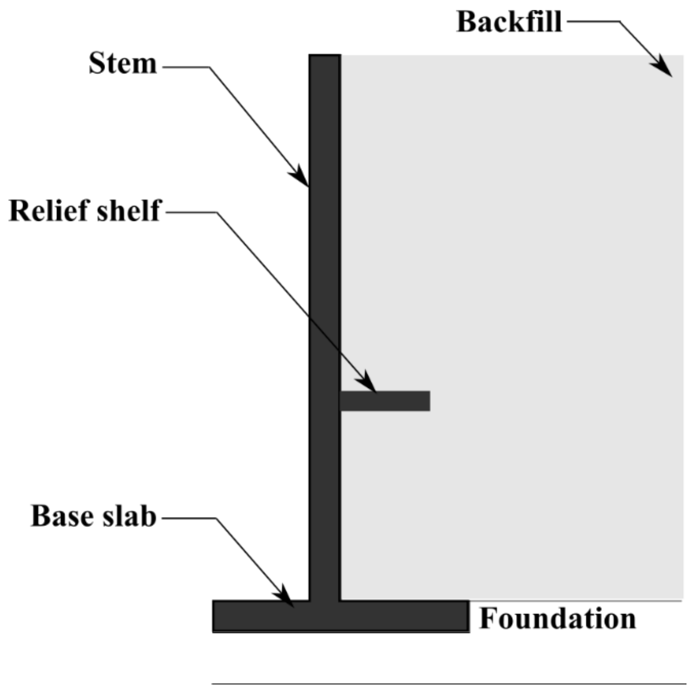


Figure 1.1. Retaining wall with relief shelf

1.3. Problem statement

Though the previous research reports using relief shelves to increase the stability of backfill materials improving the strength of retaining walls, the scope of these studies is quite limited due to the complexity of this practice which involves several parameters such as size, number and location of relief shelves within the backfill materials in the design criteria. Furthermore, the previous studies were mainly focused on non-cohesive backfill material, but this study examines the influence of relief shelves on the stability of retaining walls in cohesive soils for several combinations of relief shelves focusing on size, number, and location of the relief shelves within the backfill materials.

Most of these studies were associated with granular non-cohesive backfill materials, and no previous research has investigated the stability of such walls with cohesive backfills. But, one might encounter a situation in which retaining wall is to be backfilled with cohesive material; because there are many regions which contain cohesive material along with mountain ranges and other regions where retaining wall may be recommended to be constructed, and the use of cohesionless material to be used as backfill could be prohibited due to lack of material and high transportation cost of these materials. Moreover, studies have shown that with the increase of cohesion in the backfill, the probability of damage by the earthquake was found to be reduced, Zamiran and Osouli (2018). Similarly, other studies showed that there was a significant reduction in seismic earth pressure and wall displacement with the increase in cohesion of backfill, WANG et al. (2008).

Also, the use of some soil reinforcement methods developed like nailing, which require a long free distance behind the retaining wall for the construction purpose, are preferred commonly by many engineers all over the world; but there can be some difficulties or obstructions while building these types of walls, for example when the backfill is too narrow for their application. To overcome this problem, an effective solution could be the construction retaining walls with the provision of relief shelves.

Therefore, a dedicated study on this kind of retaining wall with the condition of cohesive backfill was required. So, the present study is intended to understand the performance of such walls with cohesive backfill and to study the influence of the pressure relief shelves on the stability of the wall. In this regard, Plaxis 2D (two-dimensional finite element software) is employed to carry out a parametric study on the relief shelves to study the influence of several parameters like size and location of the shelf on the stability of the wall. For this purpose, several models are intended to be prepared and analyzed to observe the effect of the described parameters of relief shelves on the distribution of lateral active earth pressure, total lateral thrust, bending moment, shear stress, overturning movement at the top, sliding at the base of the wall, and finally factor of safety against sliding and overturning for the cases with optimum dimensions of relief shelves. The models are broadly classified as retaining walls with a single relief shelf and retaining wall with two relief shelves. Within each case, dimensions of the parameters of relief shelf such as location, width, and thickness are varied to examine their effect on the stability of retaining wall, by interpreting the results described above. Moreover, the results of retaining wall without, with one and two shelves will also be compared to observe the effect of the number of shelves on the stability of the wall.

1.3. Objectives of the research work

- To investigate the relief shelves strengthened retaining walls using numerical simulation (PLAXIS 2D), while clayey soil is used as backfill materials.

1.4. Contents of the thesis

Chapter. 1: This chapter describes the precise summary of the research work.

Chapter. 2: This chapter reports literature review, highlighting the features of simple retaining walls and relief shelves supported retaining walls.

Chapter. 3: This chapter discusses the research methodology, followed to achieve the set objectives of the research work.

Chapter. 4: This chapter reports the results and discussions as a result of finite element analysis

Chapter. 5: This chapter summarizes the conclusions and few key recommendations, obtained from the study.

Chapter. 6: This chapter reports the references related to the thesis.

Chapter. 2

2. LITERATURE REVIEW

2.1 General

Continuous experimentation and research are being conducted on the different types of retaining walls to achieve maximum possible economy, develop a quick and easy method of construction, get reduced section sizes of components of the wall and eventually to construct the wall of maximum stability, durability, and strength. This requires techniques that can effectively decrease the earth's pressure applied on the wall by backfill, for which various methods and cross-sections of retaining wall have been developed and proposed. Tie walls, anchored walls, reinforced soil walls, geo-grid reinforced soil wall, geotextile reinforced clay retaining wall, braced walls, etc. are some of the special types of retaining walls constructed to achieve above-mentioned results. All of them have both some advantages along with some disadvantages. Lots of investigations have been carried out related to these walls.

Gabion walls and gravity retaining walls are the ones mostly used which are quite bulky in size. Some situations require contractors to build high retaining walls, for which the construction of massive gravity and gabion walls may not be viable due to economical and spatial restrictions. A cantilever retaining wall might be a better choice for such conditions, where higher backfills are to be retained. As these walls are to be designed for higher earth pressures, several design practices have been developed and recommended to increase the stability of the wall, such as counterfort and buttress retaining walls, and other modifications like soil nailing, providing base key, and batter piles, etc. Providing small slabs monolithically with the wall stem extending into the backfill is another but least studied technique to decrease the magnitude of total lateral earth thrust, which eventually decreases the overturning moment, resulting in the relatively economical design of retaining wall along with greater stability.

2.2 Lateral earth pressure

When a retaining structure retains a mass of soil, the retained mass of soil applies a thrust on the wall by its tendency to slide down and be in its natural slope (controlled by repose angle of soil). The factors affecting its magnitude are properties of backfill soil and wall displacement. If the wall rigidly fixed (no displacement), the pressure then applied on the wall is known as the at-rest earth pressure. If the wall is displaced away from the retained soil, a part of the retained backfill would slide down by tending to move apart from the rest, which exerts a pressure on the wall known as active earth pressure. While the pressure exerted on the wall is referred to as passive earth pressure if the backfill experiences pressure due to the movement of the wall towards it. A retaining wall is therefore designed to withstand or resist the forces and moments caused by active, at rest, passive earth pressures, or a combination of them depending upon the boundary conditions taken for design.

The factors on which the magnitude of earth pressure depends, are the equilibrium state of the soil, water table condition, and shear strength properties of backfill soil. Two types of states of equilibrium of soil can be encountered. One is an elastic equilibrium state, which due to small change in stress develops small strain which is reversible. The second one is the plastic equilibrium state, in which relatively larger stresses produce larger strains that are irreversible. The strain state associated with earth pressure calculations consists of three groups. At rest state is the case, in which no lateral displacement occurs with an elastic equilibrium state of the soil, as shown in Figure 2.1. (a), while Figures 2.1. (b) and (c) demonstrate active and passive states, respectively. An active state is the one, in which a state of plastic equilibrium is achieved when the wall moves away from the backfill due to the pressure exerted on it. While in the passive state, the plastic equilibrium state is achieved when the wall moves towards the backfill.

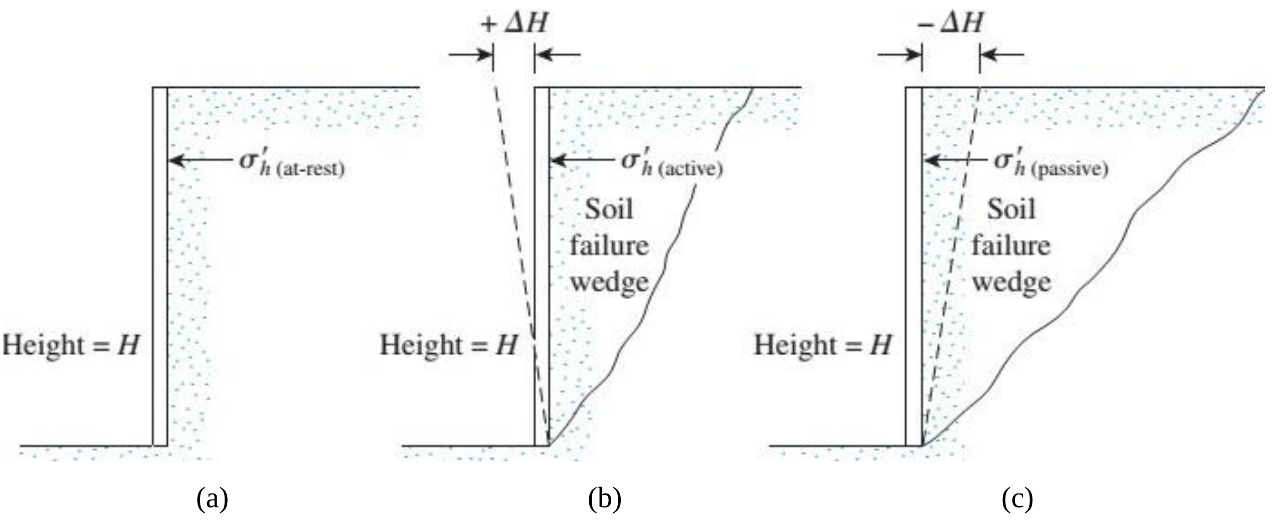


Figure 2.1. (a). At rest, (b). Active, and (c). Passive stress state

Among many theories that were proposed to determine the active and passive earth pressure, two have been adopted universally, which are Rankine's (1857) and Coulomb's (1776) theories. It can be easily shown that the Rankine's (1857) method is a special case of Coulomb's method after making appropriate substitutions, therefore, the brief, information of both the theories have been provided here.

2.2.1. Rankine's earth pressure theory

Rankine (1857) considered the equilibrium of a soil element within a soil mass bounded by a plane surface. The theory is based on some assumptions listed below.

i. The soil is semi-infinite and homogeneous.
ii. The soil is non-cohesive and dry.
iii. The surface of the ground is a plane (inclined or horizontal).
iv. The back face of the retaining wall is smooth and vertical.
v. The backfill soil is in a state of plastic equilibrium.

There is an important terminology Coefficient of earth Pressure (K) which is defined as the ratio between the effective horizontal stress (σ_h) and the effective vertical stress (σ_v). The coefficient of earth pressure at rest (K_0) is not a constant soil parameter but depends upon the history of stress applied on the soil. K_0 however, for NC (normally consolidated) soils can be taken as a constant and less than unity, where σ_v is the major principal effective stress and is greater than σ_h. As the soil becomes overconsolidated, the value of K_0 increases gradually and can become greater than one, when the σ_h exceeds σ_v. Many researchers have proposed empirical relationships for this parameter over the years. For perfectly elastic materials,

$$K_0 = \frac{v}{1 - v} \quad \text{(Eq - 1)}$$

Where, v = Poisson's ratio of soil

For normally consolidated loose sands with the angle of friction (∅),

$$K_0 = 1 - \sin\emptyset \quad \text{(Eq - 2)}$$

For densely compacted sands,

$$K_0 = (1 - \sin\emptyset) + 0.55\left(\frac{\rho_{compact}}{\rho_{min}} - 1\right) \quad \text{(Eq - 3)}$$

Where $\rho_{compact}$ is compacted dry density and ρ_{min} is the minimum dry density (loosest state) of sand. Rankine's active earth pressure is mobilized by relieving σ_h and increasing σ_v

in soil until plastic equilibrium is reached (the soil mass is at impending failure with σ_v as the major principal stress). Mohr's circle reveals failure planes developing at angles of θ with horizontal for the examination of the Rankine active earth pressure where,

$$\theta = 45 + \frac{\emptyset}{2} \quad \text{(Eq - 4)}$$

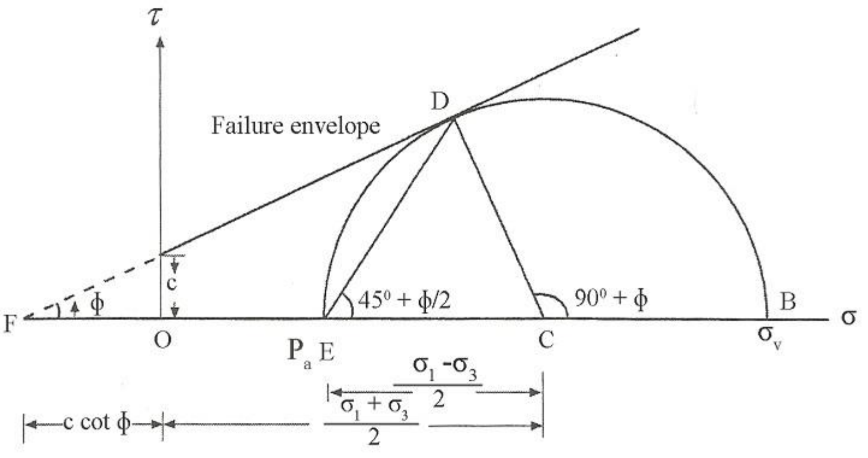


Figure 2.2. Mohr's failure envelope

From the failure envelope in Figure 2.2,

$$K_a = \frac{1 - \sin\emptyset}{1 + \sin\emptyset} = \tan^2(45 - \emptyset/2) \quad \text{(Eq - 5)}$$

So,

$$P_a = \sigma \,.\, z \,.\, K_a - 2\,c'\sqrt{K_a} \quad \text{(Eq - 6)}$$

Careful consideration of the above equation will reveal that in case of active earth pressure on the wall, the soil will be in tension supported by its cohesive strength c' up to a depth of,

$$Z_0 = \frac{2\,c}{\gamma\sqrt{K_a}} \quad \text{(Eq - 7)}$$

Finally, the total active force on the wall per unit length of the wall is given by,

$$P_a = \int_{Z_0}^{H} P_a \,.\, dz = \frac{1}{2} K_a \gamma \, (H - Z_0)^2 \quad \text{(Eq - 8)}$$

The force P_a is horizontal and acts at $(1/3)$ of $(H\text{-}Z_0)$ from the bottom of the wall.

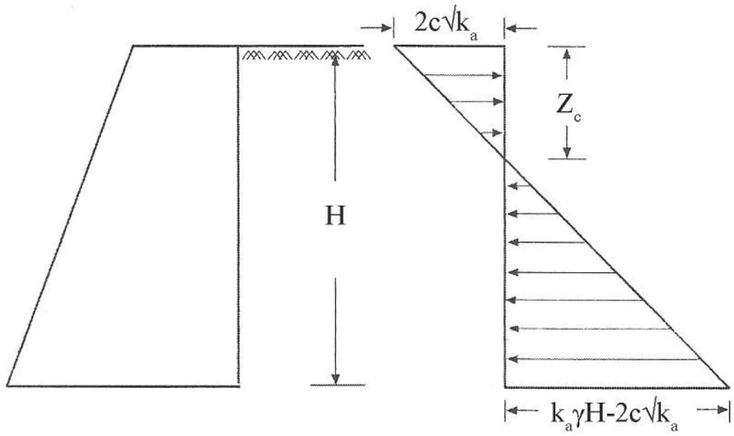


Figure 2.3. Rankine's active earth pressure distribution

Rankine's (1857) passive earth pressure is mobilized by increasing σ_h and relieving σ_v in the soil until plastic equilibrium is reached i.e. the soil mass is at impending failure with σ_h as the major principal stress. Examination of the Rankine's passive Mohr's circle reveals failure planes developing at angles of (90 – θ) with respect to the horizontal where,

$$\theta = 45 - \frac{\emptyset}{2} \qquad \text{(Eq - 9)}$$

From the Mohr failure envelope,

$$K_p = \frac{1 - \sin(\emptyset)}{1 + \sin(\emptyset)} = \tan^2(45 + \emptyset/2) \qquad \text{(Eq - 10)}$$

So that,

$$P_p = \sigma \cdot z \cdot K_p + 2\, c' \sqrt{K_p} \qquad \text{(Eq - 11)}$$

Total active force per unit on the wall is given by,

$$P_p = \int_0^H P_p \cdot dz = \frac{1}{2} K_p \cdot \gamma \cdot H^2 + 2 \cdot c \cdot H \sqrt{K_p} \qquad \text{(Eq - 12)}$$

The two components of the force Pp are horizontal and act at distances of H/3 and H/2 from wall's bottom.

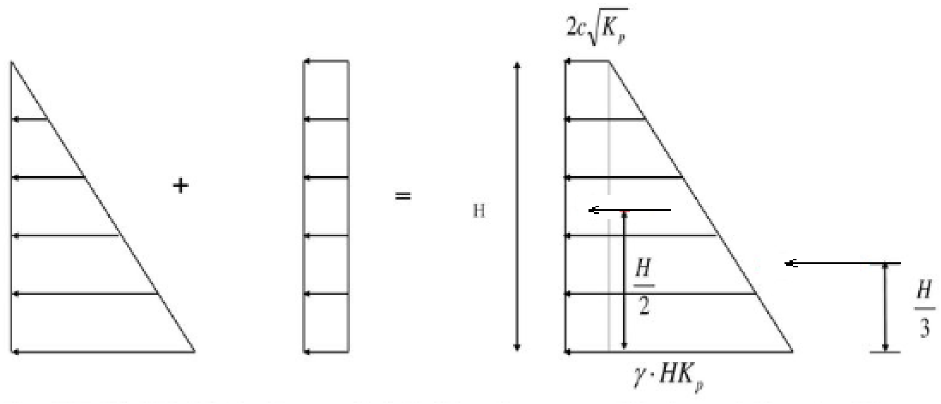


Figure 2.4. Rankine's passive earth pressure distribution

2.2.2. Coulomb's earth pressure theory

The basis of Coulomb's (1776) theory is the concept of the failure plane spreading diagonally backward and upward and in the backfill. This creates a triangle-shaped mass of soil, called a sliding wedge, between the back face of retaining wall and the plane of failure of inclination (ρ) with horizontal. The wedge would move apart from the rest of the backfill mass and slide away if the retaining structure is removed. Several forces will be acting on this wedge in different directions depending upon its movement (Figure 2.5).

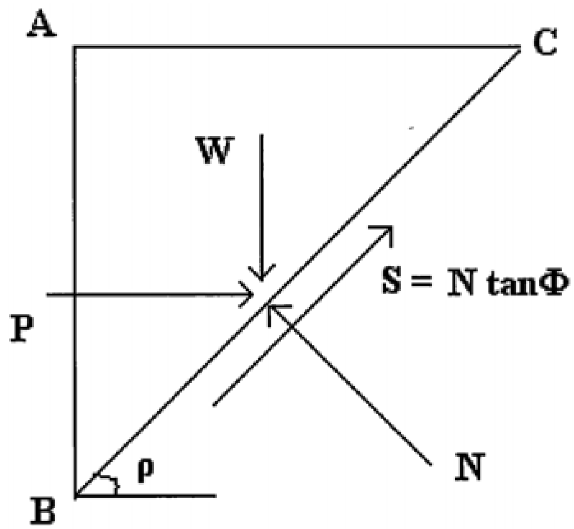


Figure 2.5. Forces acting on the wedge of soil

A free-body diagram showing the sliding soil wedge under the influence of several forces can be seen in Figure 2.5. The forces include the weight of the wedge (W) which is acting at the centroid of the resulting triangle BCA, a normal force (N) acting perpendicular to the failure plane applied by the soil which is at the right side of plane BC, and shear force (S) acting at the failure plane which is produced to prevent the sliding of the wedge away from the rest of the backfill. These forces are required to be equalized by another force (P), that is supposed to act concurrently with other acting forces like N, S, and W, and in the horizontal direction. The get the value of P, N and S must be substituted with another force known as resultant force (R), which would be inclined at an angle of Ø with a line perpendicular to the plane of failure. By considering the forces as a triangle we get,

$$P = W \cdot \tan(\rho - \emptyset) \qquad \text{(Eq - 13)}$$

$$W = \frac{1}{2} \cdot \gamma \cdot H^2 \cdot \cot^2 \rho \qquad \text{(Eq - 14)}$$

$$P = \frac{1}{2} \cdot H^2 \cdot \cot^2 \rho \cdot \tan(\rho - \emptyset) \qquad \text{(Eq - 15)}$$

P will be maximum when ρ is $45 + \emptyset/2$. So, after simplifying we get,

$$P = \frac{1}{2} \cdot \gamma \cdot H^2 \cdot \tan\left(45 - \frac{\emptyset}{2}\right) \qquad \text{(Eq - 16)}$$

$$P = \frac{1}{2} \cdot \gamma \cdot H^2 \cdot \sin \frac{1 - sin\emptyset}{1 + sin\emptyset} \qquad \text{(Eq - 17)}$$

$$P = \frac{1}{2} \cdot \gamma \cdot H^2 \cdot K_a \qquad \text{(Eq - 18)}$$

The above equation is similar to Rankine's (1857) equation for a leveled backfill.

2.3. Stability of retaining wall

To analyze for stability requirements, the actual earth pressure on structure and resistance offered by structure due to its weight and other reactions are considered. Retaining wall's stability is analyzed for following;

a. Stability of wall against overturning:

This is to ensure that resultant of the all forces do not overturn the base of retaining wall. The factor of safety (FOS) against overturning ranging from 1.5 to 2 is usually desired, and given by,

$$FOS = \frac{\text{Sum of moments Resisting}}{\text{Sum of moments overturning}} \qquad \text{(Eq - 19)}$$

b. Stability of wall against sliding:

The FOS of a retaining wall against sliding must be greater than 1.5. If it is less than 1.5 then key or cut off the wall is designed at the bottom of the base slab to increase FOS against sliding by preventing the lateral movement of the structure, and is given by,

$$FOS = \frac{\mu \, . \, R_v}{R_h} \qquad \text{(Eq - 20)}$$

Where, R_v and R_h are vertical and horizontal components of R, respectively, and μ is a coefficient of shear resistance and normally taken as 0.5 for concrete.

c. Maximum pressure is present on the toe slab and minimum pressure on the heel slab:

Maximum pressure on the toe of the slab must be smaller than the safe bearing capacity and minimum pressure on the heel of the slab should be compressive in nature. The pressure exerted at the toe of the wall should not surpass the allowable bearing strength of the foundation soil. The linear distribution of the pressure at the footing is assumed, and its maximum value is given by,

$$P_{max} = \frac{R_v}{b} \left(1 + \frac{6e}{b}\right) \qquad \text{(Eq - 21)}$$

Where R_v is the vertical force and e is the eccentricity of the applied force from the centroid of the base. The FOS against bearing failure is given by,

$$FOS = \frac{q_m}{P_{max}} \qquad \text{(Eq - 22)}$$

Where q_m is the bearing capacity of the foundation. FOS against bearing capacity failure of 3 is normally required, provided that the settlement is within the specified limits.

2.4. Provision of relief shelf to retaining wall

The provision of small horizontal slabs known as relief shelves monolithically with the stem of the wall has found to reduce the magnitude of lateral active earth pressure (P_a) and total lateral thrust (P) on the wall. This would eventually cause a reduction in overturning moment on the wall, which would enhance the strength and stability of the wall, and help in developing an economical design of retaining structure to withstand particularly high earth pressures. According to Jumikis (1964), the distribution of P_a on the wall below the shelf would start from zero, as there was nothing above it (see Figure 2.6). According to the author, if the width of the shelf is larger than (H - T - h) tan (45° + $\emptyset$/2), the failure plane which is sloped at $(45° + \emptyset/2)^0$ with the horizontal, cannot be produced, as it has to pass through the shelf. For a non-cohesive soil, P_a exerted on a retaining wall can be estimated by considering different wedges of the soil mass above and below the shelf.

The pressure distribution diagram changes from a single triangle to two triangles from the hill to the relief shelf and from the relief shelf to top of the wall. It is assumed that the Rankine's (1857) P_a is acting along a vertical plane of the stem.

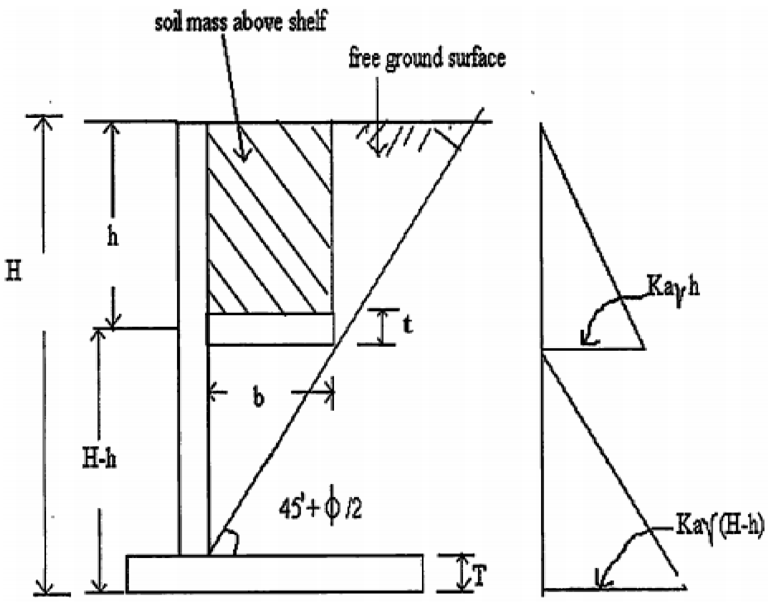


Figure 2.6. active earth pressure distribution with the provision of single relief shelf

The forces exerted by the weight of the soil body above the heel and shelves and the weight of the structural members produce resisting moments. The usually required value of FOS with respect to overturning is 1.5 to 2 for cantilever section but it is found that the FOS increases significantly by providing shelf to about 2 to 3. P_a is assumed to be zero at the location of the relief shelf. Raychaudhuri (1974) studied the impact of providing relief shelves by removing the mass of soil above the shelf from the sliding wedge. Though, the transformation of the center of gravity of failed soil wedge was not considered. The relief shelf is constructed monolithically with the stem so one end of relief shelf is properly fixed to the stem and the other end is free. The lateral movement of the relief shelf is resisted by friction developed between the relief shelf and the soil above and below the relief shelf.

2.5. Previous studies on retaining wall with relief shelves

Jumikis (1964) investigated the influence of the provision of one and two relief shelves to a counterfort retaining wall to enhance its firmness and stability. The author prolonged the shelves up to the failure planes and observed that the lateral active earth pressure (P_a) acting on the wall was significantly reduced by the addition of relief shelf with the stem of the wall. The author concluded that the stability of a counterfort retaining wall may be significantly increased by the provision of relief shelve by extending them to the rapture surface. The author further concluded that this practice can produce economical designs of retaining walls because less material will then be used in the retaining wall, as compared to the massive walls without shelves. Moreover, theoretical methods for estimating the stability of the counterfort retaining wall when relief shelves are constructed. The illustration can be seen in Figure 2.7 below. It was suggested that for high retaining walls, more than one relief shelf would be a good solution to the stability problem of the wall. Also, the relief shelves for counterfort retaining walls can be constructed up to the length of counterfort.

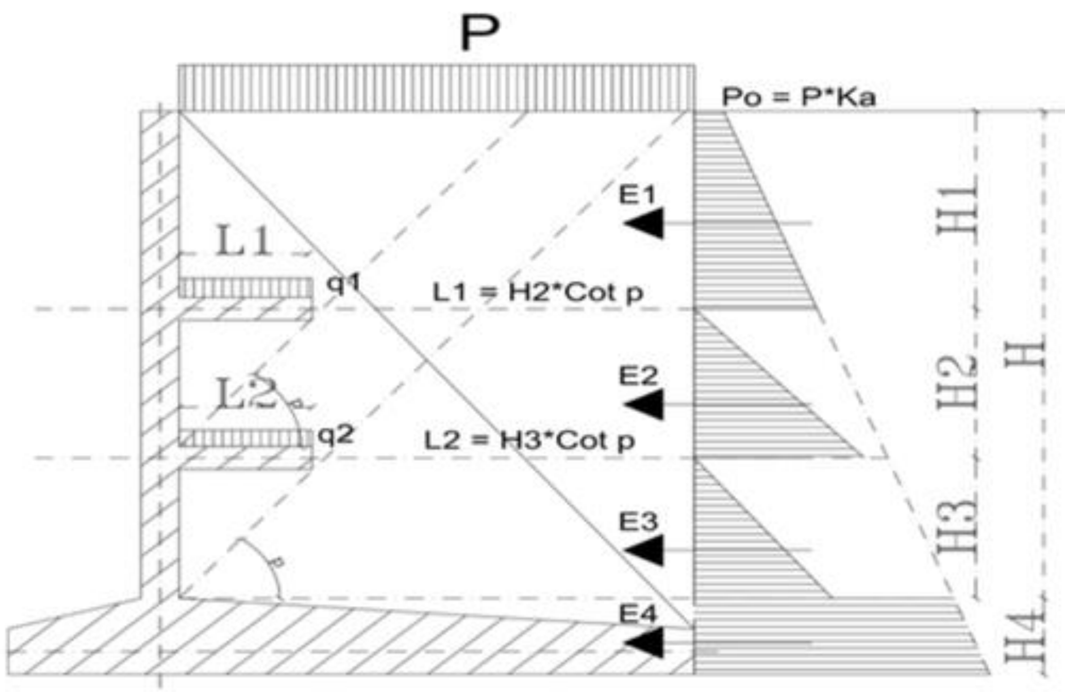


Figure 2.7. Idea of a counterfort retaining wall with two relief shelves

Chaudhuri et al. (1973) considered Coulomb's (1776) earth pressure theory, in order to analyze and design this category of retaining wall for cohesionless soil. He conducted an experimental study for checking the stability of this kind of wall. The author developed a method to quantify the reduction in total active earth pressure (P_a) on the wall and how the distribution of active pressure is developed when the relief shelf is connected with the stem of the wall. Readymade charts were developed for different combinations of widths and locations of the shelf to estimate the reduction factors. The author also stated that the provision of the base key may not be necessary when a relief shelf is provided, which reduced significantly the magnitude of P_a on the wall. One of the limitations in his study was the absence of experimentation on this type of wall to observe the effect of the shelf on its overturning.

After a few years, experimental research was carried out by **Yakovlev (1974)** for the determination of P_a on retaining wall with relief shelves. The experimentations were performed in a 400 kg open panel, the face of which consisted of 10*10 cm blocks bolted to a frame of several beams. The dimensions of the model were 109 cm, 100 cm, and 177 cm for height, width, and length, respectively. To measure pressures on walls and shelves, 12 number of pressure cells were employed which were attached at different locations on the wall and shelves. The author found that an internal surface of sliding began to start at the endpoint of the relief shelf, for wall displacement. Between the wall, internal sliding surface, and the shelf, the soil particles did not displace while the displacement of the stem of the wall, and the state of equilibrium was not produced in that backfill zone. It was found that for the same location of the shelf, the size of the sliding zone increased with an increase of the width of the shelf. Moreover, particle displacements were maximum in the regions between the shelf and external sliding surface. The author observed that an increase in stresses was caused by the load outside the sliding wedge.

While comparing to the theoretical methods, it was found that the pressure on the wall beneath the shelf was more than that of the analytical approach, while near the bottom of the wall pressure was less. The resultant of the pressure on the lower part of the wall reduced continuously during the movement of the wall until the displacement reached 0.005 to 0.01 of the wall total height. It was observed that at smaller depths, the pressure was found to be increased when larger widths of the wall were used. Resultant values of active earth pressure

(P_a) on the wall were found to be less than that of the analytical approach before the movement of the wall, but gradually increased an reached the theoretical value after the movement started. The same phenomenon was observed for retaining walls with relief shelves. The pressure on the middle part of the wall was always greater than the calculated values. It started to decrease when the displacement of the wall reached 4.5 mm but still was greater than the calculated ones. The experimental overturning moment at the base of the wall was greater than that of calculated moments because the resultant force acted a higher location in the former case. The pressure recorded on a cell located at the upper portion of the lower shelf, tend to decrease up to 30 percent due to arching phenomenon and started to increase as the displacement reached 0.004 of the wall height, but never surpasses the initial value.

Phatak and Patil (1975) modified the theoretical method of measurement of P_a on the retaining wall with relief shelf by Rankine's theory (1857), by taking into account the transformation in the position of the center of gravity of the failure wedge above the shelf which was initially ignored by Chauduri (1973). The author found that how the center of gravity would shift due to the provision of relief shelf, and concluded that, a significant amount of reduction in the overturning moment is achieved at the base of the wall due to a decrease in total lateral thrust and moment arm. The author also determined that the location of the application of resultant force is controlled by the angle of internal friction, the width of the shelf, and failure plane angle in backfill with horizontal.

Varghese (2005) stated that, when the height of the retaining wall exceeds about 10 m, the design of a simple cantilever or gravity wall becomes very uneconomical due to high earth pressure. In such cases, soil nailing and anchoring might be a good solution to overcome greater earth pressures on the wall. Other than that, the provision of relief shelves could also be a feasible solution to the said problem, which can also be provided with buttress walls in between the buttresses to enhance the stability of retaining wall. They are usually constructed after the backfilling of soil up to their level. Moreover, in some cases, they might be required to be braced at the far end by means of piles or columns. The pressure diagram will be interrupted at the level of the platform and almost starts from zero beneath the platform.

Padhye and Ullagaddi (2011) adopted Coulomb's method to present a theoretical study of cantilever retaining wall with a single pressure relief shelf and proved that coulomb's theory can be successfully adopted to analyze earth pressure on a retaining wall with relief shelves. In the analysis, the authors proved that with the provision of relief shelf, the active earth pressure (P_a) and moment arm were significantly reduced, which eventually the overturning moment about the base.

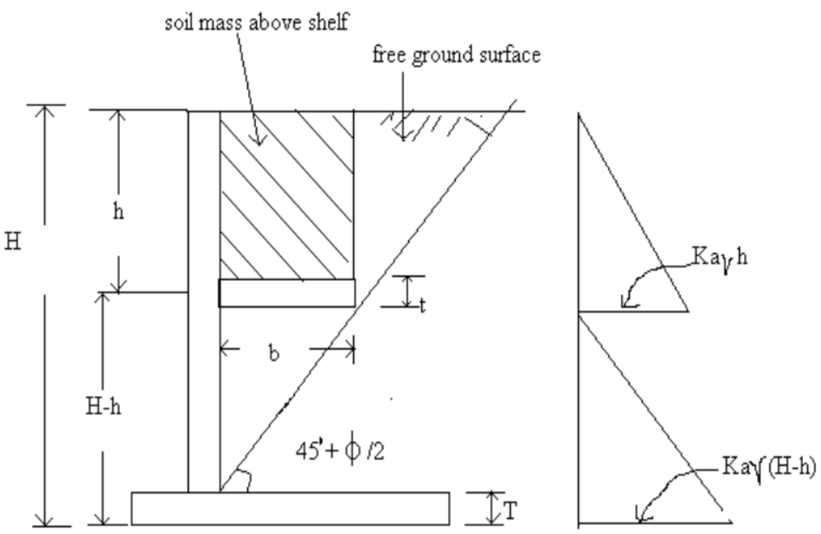


Figure 2.8. Concept of active earth pressure distribution with one relief shelf

The author studied the influence of the relief shelf by removing the mass of soil above the relief shelf from the failure wedge. It was found that, when the shelf's width (b) of (H - T - h)tan (45- $\emptyset/2$) is used, it would intersect the failure plane initiating from the base of the wall. The author calculated the decrease in the magnitude of P_a by the addition of relief shelf to the stem by carrying out stability analysis of soil wedges using formulations made by Coulomb and expressed it as a fraction of total P_a for a simple retaining wall with no relief shelf. Through force triangulation method,

$$P = W\left(\frac{\sin(\theta - \emptyset)}{\sin(\theta + \rho - \emptyset)}\right) \qquad \text{(Eq - 23)}$$

Where ρ is the inclination of the failure plane with horizontal, θ is the angle made by the back face of the wall with the vertical, ∅ is the angle of internal friction of backfill soil. The above equation is only valid when the angle of the slope of the backfill is zero. Hence the weight of the wedge that causes slide becomes,

$$\left(\frac{\gamma}{2}\cot\rho - \gamma \,.\, \beta \,.\, \delta\right) H^2 \qquad \text{(Eq - 24)}$$

Where β is equal to b/H and δ is location factor and equal to h/H. The value of reduced active pressure Pr was found to be,

$$P_r = \frac{\left(\frac{\gamma}{2}\cot(\rho) - \gamma \,.\, \beta \,.\, \delta\right) . \sin(\rho - \emptyset)\, H^2}{\cos(\theta - \rho + \emptyset)} \qquad \text{(Eq - 25)}$$

Shinde and Watve (2015) modeled a 7 m high cantilever retaining wall with a cohesionless backfill material in a finite element modeling software STAAD Pro to analyze the effect of the addition of relief shelf on wall stability. The study revealed that the best location for the construction of the shelf would by between 0.4 to 0.5 of the height of the wall from the top. That position of the shelf found to produce a maximum reduction in lateral thrust and bending moment along the stem of the wall. Maximum reduction up to 41.5 percent was obtained when location factor 0.5 was used, it increased when the shelf was lowered at location 0.8 of the height from the top. Moreover, with the increase of the shelf's width displacement of the wall reduced significantly enhancing the stability of the wall.

Shehata (2016) carried out a study by analyzing finite element models of a retaining wall of height 10 m and base 5 m in Plaxis 2D. The analysis was divided broadly into three groups and consisted of different combinations of widths, locations, and thicknesses of relief shelves. A significant influence on the earth pressure (P_a) distribution was observed with the addition of relief shelves to the wall. In the first group, the effect of providing one or two shelves was studied. Secondly, in the second group of analysis, the effect of the shelf's rigidity was studied by keeping the location of the shelf constant and varying its width and thickness. At last, the final group of analysis consisted of studying the influence of the location of the shelf, by keeping thickness and width constant and changing the location of the shelf from top to bottom of the wall height. The effects of different parameters were studied by observing the change in P_a and bending moment on the wall stem. A significant reduction in both of them was observed. The active earth pressure started with almost zero beneath the shelf with a smaller slope as that of a simple wall.

Shelf of smaller thickness deflected more as compared to the one with larger thickness. To the deflection of the shelf, vertical pressure on the soil below the shelf increased and produced larger earth pressures beneath the shelf. The same trend was followed by a wall with two relief shelves. Regarding the width of the shelf, it was found that when smaller widths were used which could not be extended to the rapture surface, greater earth pressures were produced. Whereas, when the shelf's width of 2 m and 3 m were used which were extended to the rapture surface, the distributions of earth pressure were similar to each other. Finally, it was suggested after the analysis that the best location of the shelf is 0.30 of the wall height from the top. The overturning moment on the wall stem was found to increase when the location of the shelf was increased from 0.2 of H to 0.8 of H. Moreover, the maximum reduction in wall overturning was obtained at location of 0.30 of H from the top.

Chauhan et al. (2016) investigated the possible reasons which could have caused the failure of a retaining wall with some relief shelves, constructed in Hyderabad city, India. A case of retaining wall failure was reported in Hyderabad, India, where retaining walls of the varying height of 10 to 13.9 m with multiple relief shelves were constructed to retain the soil. The above structure had failed a few years after the construction. Failure of such structures at few places was the reason which motivated the authors to investigate the cause of the failure of retaining walls with relief shelves at Hyderabad. The failed retaining wall was analyzed in FLAC3D, in which, the wall was modeled as an elastic material, backfill material an elastoplastic material, and the interface between wall and soil was represented using a linear spring slider system following Mohr-Coulomb failure criterion. From the numerical analysis, it was found that due to the use of high width of relief shelves, the passive pressure beneath the relief shelves had significantly increased, which had produced the unforeseen high stresses on the faces of wall stem just beneath one of the relief shelves, which caused the failure. Contrary to conventional rigid retaining cantilever walls, compressive stresses were recorded on the face of the stem towards the backfill and tensile stresses on the opposite face. Authors, therefore, inferred that the unanticipated stresses might have gone unnoticed during the design of the retaining wall, which resulted in cracking of the stem of the retaining wall.

The author stated that providing five relief shelves had divided the entire retaining wall into six small sections, and it was observed that P_a in the top two sections increased, but in the bottom two sections, P_a decreased with the increase in the shelf's width. A range of 43.5 - 47.9 percent of total thrust reduction was achieved by providing relief shelves. The settlement of backfill close to the wall also decreased with the increase in width of the relief shelf. These relief shelves were working like a horizontal obstruction for the backfill vertical settlement close to the stem of the retaining wall, but their influence was found to be decreased by increasing the distance from the stem. The movement of the wall away from the backfill was also studied and it was found that the lateral displacement of the wall was reduced due to the provisions. With the increase of the shelf's width, the maximum displacement of retaining walls was reduced, which was due to the decrease of total thrust on the wall and increased weight of the wall due to relief shelves. The deflection of relief shelves for the whole retaining wall was found to increase and was maximum for the lowest located relief shelf for all the cases of retaining walls with relief shelves. Finally, the results also showed that passive pressure ($P_{p)}$ was also getting introduced just below the relief shelves. More the width of relief shelf higher P_p was acting on the retaining wall.

Dharshan and Keerthi (2016) analyzed cantilever earth retaining wall of height 4 m with and without pressure relief shelf employing commercially available finite element packages (SAP2000). In the study, the authors conducted a comparative study of the stability of conventional cantilever retaining wall with and without pressure relief shelf. The authors varied the positions of pressure relief shelves (placed them at H/3, H/2, 2H/3 positions) to analyze the performance of retaining wall. The moments developed in the wall with shelves were observed less compared to retaining wall without shelves. During the absence of a pressure relief shelf, 17 percent more moments were recorded by SAP analysis in comparison with the manual (conventional) method of analysis of the cantilever wall. With the provision of relief shelves at H/3, H/2, and 2H/3 positions of the stem, 22 percent, 33.46 percent, and 41.53 percent of reduction of moments are recorded in comparison to the moments of cantilever retaining wall without shelf. Due to the reduction in the moments, the stability of the cantilever retaining wall was also increased against overturning and sliding. Displacement of a stem without pressure relief shelf was recorded as 8.2 mm while for with shelf condition 6.7 mm, 5.4 mm, and 4.6 mm displacement of the stem were recorded at H/3, H/2, and 2H/3 positions respectively. The authors also concluded that the best location among all studies is 2/3 of the height of the wall from the top for a single relief shelf.

Khan et al. (2016) evaluated the impact of shelves on active earth pressure (P_a) both by physical model laboratory testing and by numerical modeling in ABAQUS. In the laboratory, small-scale model tests were conducted in a steel tank with length, width, and height of 1.2 m, 0.31 m, and 0.7 m, respectively, with sand as backfill material with a relative density of 80 percent (achieved by modified traveling pluviator). along with a static surcharge load of 10-50 kPa with an increment of 10 kPa using a hydraulic actuator. After analysis, it was observed that P_a distribution on the wall significantly reduced by providing relief shelves. The reason the researchers provided was most of the soil overburden and static surcharge load was taken by the shelves which resulted in the reduction in P_a on the wall by 18 percent when using a single shelf and 26 percent while using double relief shelves. The authors also concluded that among all the cases studied, relief shelf of width 0.5 m and thickness 0.3 m placed at position factor of 0.55 is most effective in P_a reduction.

For numerical modeling, a 6 m high retaining wall in all tests, was modeled as linear elastic isotropic material, while foundation and backfill soil as an elastic perfectly plastic material following Mohr-Coulomb criterion in ABAQUS software. All the model retaining walls were analyzed with 50 kPa surcharge loading on the surface, and the effect of thickness, position, and width of the relief shelf was studied for a single relief case. The effect of relief shelf thickness ranging from 0.2-0.6 m, and positioned at a location 2 m or 4 m were studied for the case of constant width of relief shelf of 1.5 m. For two relief shelves case, thickness (0.3 m), width (1.5 m), and position of relief shelves (2 m and 4 m, from top) were maintained constant. The earth pressure was reduced significantly by the provision of relief shelves, and the reason the authors stated was, that probably the major part of the soil overburden and surcharge load was taken by the relief shelf which resulted in the reduction of P_a on the wall, and therefore, enhancing the stability of the wall. Reduction of P_a on the wall by 18 percent when using a single shelf and 26 percent while using double relief shelves was observed. It was also observed that surface settlement was also reduced by the provision of relief shelves. To evaluate the effect of the width of shelves, a parametric study was conducted by varying the width from 0.5 m to 2 m, and it was found that with the increase of width, overall P_a on the wall was decreased.

Chougule et al. (2017) carried out a detailed analysis of the stability of cantilever retaining wall having relief shelves with a cohesionless material using both analytical and numerical modeling approaches by STAAD Pro. The analysis consisted of three models, that were cantilever walls without shelf, with a single shelf, and with double shelves. The study concluded that the optimum location of the shelf is 7/12 of the height of the wall for a single relief shelf, and 4/12 and 7/12 of the wall height for two relief shelves, from the top of retaining wall. Moreover, it was concluded that the higher the wall height higher the percentage of material saving, and the wall with two shelves were found to be more economical and stable as compared to the one with a single shelf.

By evaluating the research work carried out by researchers presented above, it can be inferred that there is still a scope to perform the laboratory and numerical model analyses on this kind of retaining wall with relief shelves. Firstly, a detailed study on this type of wall is important as it can be the possible alternative solution to retaining wall stability, other than counterfort and buttressed walls. Secondly, previous research was associated with cohesive backfill material, and there was a lack of research on the performance of this kind of wall while retaining cohesive backfill, as it might be useful in some situations to have cohesive backfill. Due to these two reasons, the present study is focused on the parametric analysis of retaining wall with relief shelves with cohesive backfill material and will estimate the influence of dimensions of various parameters of shelves like, with location and thickness.

The present research has been planned to be conducted by numerical model analyses on commercially available software Plaxis 2D. Many researchers such as Shehata (2016), Yang and Liu (2007), Chogueur et al. (2018), Kim et al. (2010), Rouili et al. (2005), Huggins and Ravichandran (2011) have employed Plaxis to conduct the stability analysis of different types of retaining walls, and have got the desired results, successfully. Plaxis is special-purpose software designed to carry out deformation and stability analysis of structures related to soil and rock. Therefore, all the models within the scope of the present study will be made using Plaxis 2D to analyze the influence of relief shelves with cohesive backfill materials.

2.6. Introduction to Plaxis 2D

Plaxis 2D is a special-purpose finite element (FE) modeling software used by geotechnical engineers or professionals worldwide. Plaxis 2D is a two-dimensional FE software, using which many kinds of geotechnical structures and conditions can be modeled and analyzed for deformation stability. Actual conditions can be modeled either by an axisymmetric or model plane strain. The user interface involves four subprograms that are,

i. Input program.

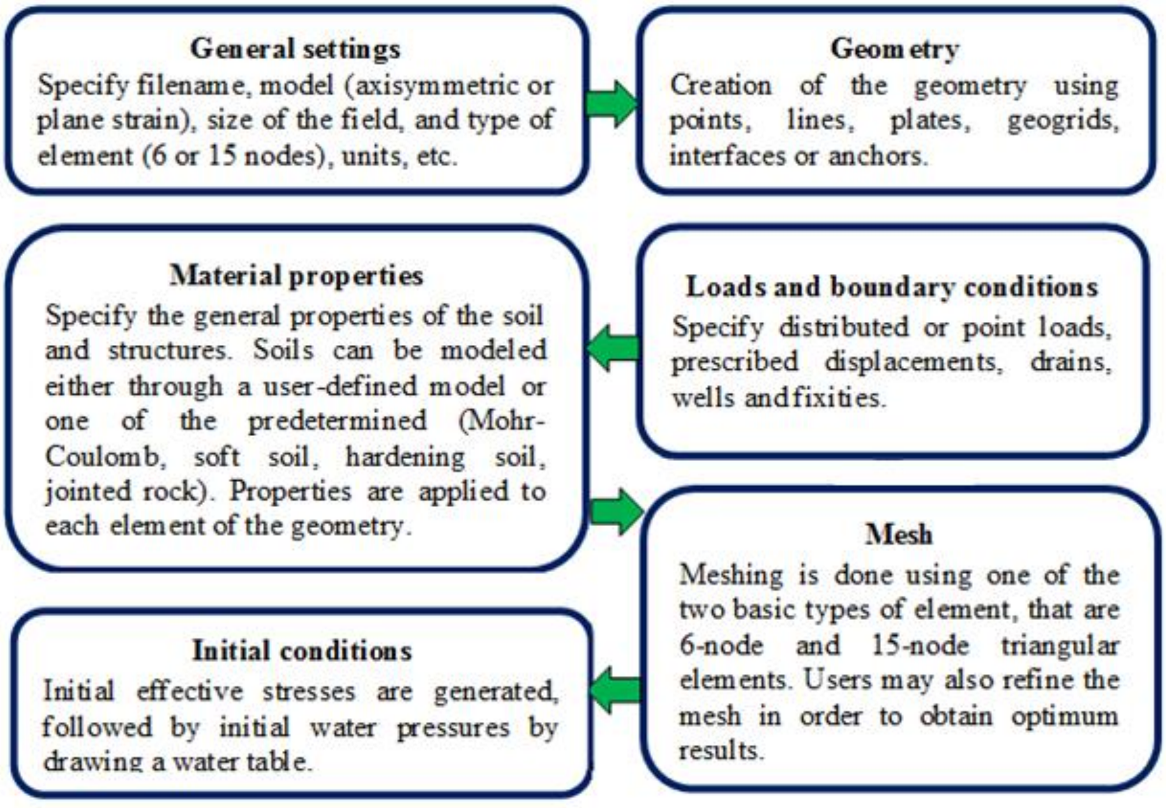
ii. Calculation program.

iii. Output program.

iv. Curves program.

2.6.1 Input program

For conducting the analysis, the user first has to generate a finite element geometrical model consists of several elements like soil bodies and structural members, specify the properties of the material used, and apply boundary conditions before generating a suitable finite element mesh. Finally, an initial state is generated by introducing initial effective stresses. The procedure is presented below.



2.6.2. Calculation program

Once the initial conditions have been generated, the next task is to describe the type of loading methods and calculations to be employed. It comprises several types of calculations such as plastic, phi reduction, consolidation, and dynamic. Moreover, the program provides the option to divide the construction process into phases to simulate real-time stages of construction, for example, deactivating the cluster to show excavation or activating to simulate surcharge. When the plastic calculation is chosen, as used in almost all the situations, the program produces some nonlinear equations, that need to be solved in every phase in an array of load steps. The program automatically selects the correct configuration to guarantee optimal results. The described process is controlled by a certain parameter that keeps efficiency, exactitude, and hardiness in equilibrium.

2.6.3. Output program

The output program allows the user to extract all of the results as a result of the calculation program, which he desires. Mostly, the results from a FE model include the node displacements, forces, stresses (within the soil, and against the structural elements). Using different representations like shadings, contour lines, arrows, results may be analyzed. Moreover, results may also be obtained in tables, which can also be obtained in the form of excel spreadsheets using an export option, so that any type of required interpretation can be done.

2.6.4. Material models used in FE modeling

To model the performance of soil under loading conditions with varying degrees of accuracy, several soil models being developed are employed in Plaxis. Some basic stress-strain relationships available are Hooke's law of linear and isotropic elasticity, etc., as they involve only two input parameters, i.e. Poisson's ratio (v) and Young's modulus of elasticity (E), which are normally too basic to simulate the important attributes of rock and soil behavior. Different soil models incorporated in Plaxis are as under;

i. Mohr-Coulomb model.
ii. Jointed rock model.
iii. Soil hardening model.
iv. Soft soil creep model.
v. Soft soil model.

Calculations of realistic geotechnical situations can be performed easily using the Plaxis code and available soil models in it. In this regard, Plaxis 2D can be employed for simulation of almost all types of geotechnical structures. The behavior of soil can be represented quantitively using different soil models listed above, incorporating model parameters used to quantify the soil behavior. Among all the models, the Mohr-Coulomb and Hardening soil model have been used usually by various researchers to simulate soil behavior while analyzing the stability of retaining structures. Both of them are discussed below.

2.6.4.1. Modeling of backfill and foundation soil

For the present study, the Mohr-Coulomb model has been employed as one of the most reliable and commonly used models all over the world, and renowned for providing reliable results in almost every condition.

2.6.4.1.1. Linear elastic perfectly plastic (LEPP), Mohr-Coulomb model

Soil bodies exhibit nonlinear behavior, when stress or strain variations are applied to them because the stiffness of soil depends upon stress and strain levels, and stress path and. Such features have been added to the soil models in Plaxis. One of the simple, well known, useful, and most widely used in-built models is the Mohr-Coulomb model which is a LEPP model and can be effectively employed by various researchers (Chauhan and Dasaka, 2018, Khan et al., 2016, Yang and Liu, 2007, Chogueur et al., 2018, Kim et al., 2010, and Chauhan et al., 2016) to simulate soil behavior while analyzing retaining structures' stability. The elastic portion of this model is built on isotropic elasticity behavior following Hooke's law, while the perfectly plastic part is built on the failure mode following the Mohr-Coulomb criterion (Figure 2.9).

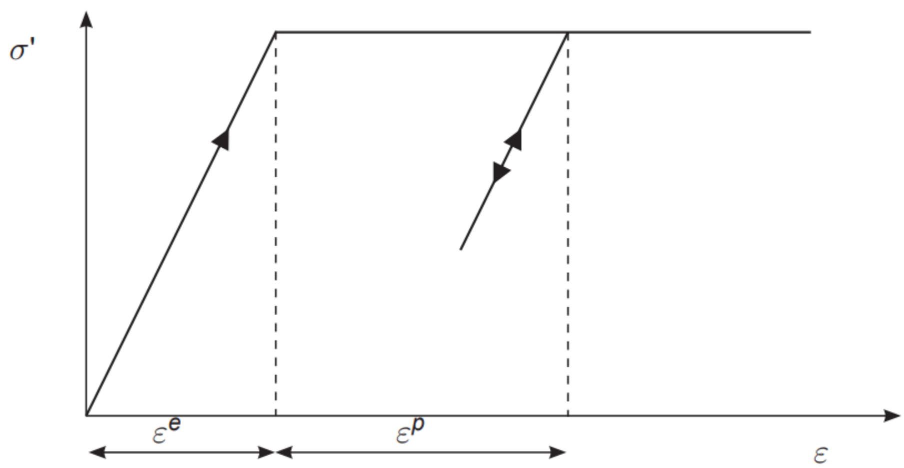


Figure 2.9. The basic idea of an elastic perfectly plastic model

Plastic behavior means when irreversible strains are developed. A perfectly plastic model is a model that as yield surface (fixed yield surface defined by model parameters), which is not affected by irreversible yielding. On the other hand, when the stress state is represented by points inside the yield surface, the behavior will be purely elastic, developing reversible strain or deformation. employed this model to simulate soil behavior for the stability analysis of retaining walls.

2.6.4.1.2. LEPP behavior

The fundamental principle of elastoplasticity is described as the rates of stress and strains that are broken into two parts, including an elastic and a plastic part. The classical theory of plasticity by Hill (1950) states that plastic strain rates and yield function’s derivative w.r.t stress are indirectly proportional relationship. This accomplishes that, perpendicular vectors to yield surface can be used to represent the plastic strain rate. This attribute of the theory is specified as associated plasticity. As far as yield functions of the Mohr-Coulomb model are considered, the concept of associated plasticity overvalues dilatancy. Therefore, other than the yield function, a plastic potential function (g) is introduced, such that,

$$\varepsilon^{\cdot p} = \lambda \, . \, \frac{\partial g}{\partial \sigma} \qquad \text{(Eq - 26)}$$

where, $\varepsilon^{\cdot p}$ is the plastic part of strain rate and λ is the plastic multiplier (in case of purely elastic behavior, λ is zero; whereas for plastic behavior λ is positive).

2.6.4.1.3. Basic parameters of the Mohr-Coulomb model

The model consists of six parameters, that can be found through basic laboratory tests on soil samples. Their list with standard units is given in table 2.1.

Table 2.1. Mohr coulomb's parameters

S. No	Name	Symbol	Unit
1	Young's modulus	E	kN/m^2
2	Poisson's ratio	υ	-
3	Cohesion	c	kN/m^2
4	Friction angle	$\emptyset$	Degrees
5	Dilatancy angle	ψ	Degrees
6	Unit weight	γ	kN/m^2

2.6.4.1.3.1. Young’s modulus (E)

It is a fundamental modulus related to the stiffness of soil for this model. The values of this parameter require special consideration due to the nonlinear behavior of geomaterials from the very beginning of loading. Moreover, the estimated values of E may be higher for shearing than for compression, and vice versa. Therefore, a steady value of stiffness at different stress levels must be used when using a constant value stiffness modulus to characterize soil's mechanical behavior.

2.6.4.1.3.2. Poisson's ratio (υ)

It is defined as the ratio of vertical strains to horizontal strains produced in a sample. The smaller initial value of the Poisson's ratio can be obtained by standard drained triaxial test, which is capable of producing a substantial rate of volume change when the axial loading juts starts. This low value is recommended for a few cases, such as particular unloading situations, but is generally for this model higher value is suggested. Moreover, for unloading conditions, it is more suitable to use values ranging from 0.15 to 0.25 (Brinkgreve et al., 2004). Furthermore, when drainage type is set as undrained, ratio describes an effective *v*; however, Plaxis automatically considers the incompressible behavior of soil. To guarantee a more compressible behavior of soil solids for undrained conditions, the effective *v* should be less than 0.35 (Brinkgreve et al., 2004).

2.6.4.1.3.3. Cohesion or undrained shear strength (c)

It is the intercept of the failure envelope line on the shear axis of the shear – axial stress graph which can be estimated using direct shear or triaxial tests. For drained type analysis, effective cohesion c' must be used along with effective ∅'. Moreover, for undrained type analysis, the cohesion parameter may be used to model the soil, where the friction angle will be zero. Moreover, the use of an effective strength parameter has an advantage that the variation of shear strength of soil because of consolidation is achieved automatically.

2.6.4.1.3.4. The angle of internal friction (∅)

This parameter is used to model the effective friction between the soil particles, which has a unit in degrees, in combination with a value of effective cohesion c' (Figure 2.10 (a)), which may be used to represent the drained behavior of soil. Similarly, for the undrained behavior of soil, internal friction of soil is zero along with cohesion which is the undrained shear strength (Figure 2.10 (b)).

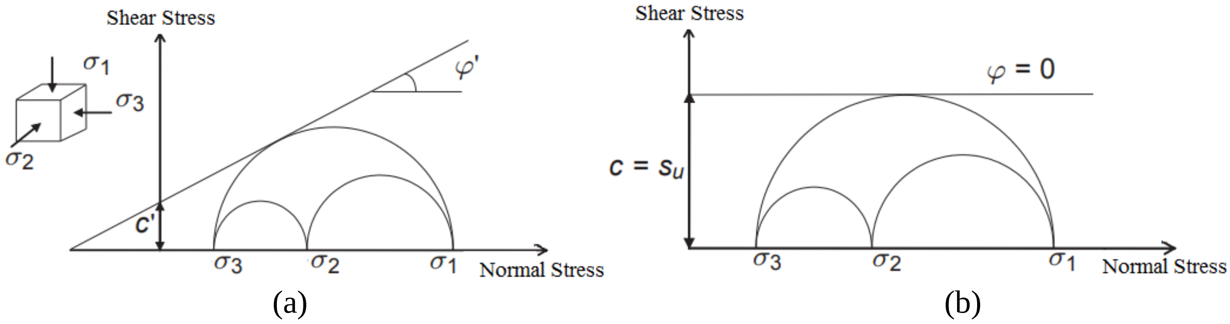


Figure 2.10. Mohr Coulomb's failure envelope for (a). drained and (b). undrained conditions

2.6.4.1.3.5. Dilatancy angle (ψ)

This parameter is another important factor that controls the plastic volumetric strain developed in the soil during plastic shearing and is expected to be constant during plastic yielding. Its unit is in degrees. Other than heavily overconsolidated layers, cohesive or clayey soils tend to show little or no dilatancy, e.g. $\psi = 0$ (Brinkgreve et al., 2004). The dilatancy of sand is controlled by both its density and friction angle. Commonly, the value of ψ of soils smaller than the friction angle. For granular soils like sands, the dilatancy angle can be obtained by $\psi = \emptyset - 30$. For internal friction angle of values less than 30°, ψ is usually taken as zero. A positive value of ψ indicates that the soil is going to dilate in drained providing shear deformation occurs.

2.6.4.1.4. Advanced parameters of the Mohr-Coulomb soil model

Some advanced features are also involved in the model, which are the increase of cohesion and stiffness with depth, and tension cut-off strength. These parameters can be defined in the advanced tab.

2.6.4.1.4.1. Tension cut off the strength

Many practical situations produce areas with some tensile stresses, for instance, soil surface close to a trench in cohesive soil can develop tensile cracks. This phenomenon shows that soil can also experience failure, not in shear but tension. Such behavior can be simulated in PLAXIS by defining the tension cut-off strength of soil, by defining the tensile strength of the soil. By default, the tensile strength of the soil is selected as zero for the Mohr-Coulomb model.

2.6.4.1.5. Hardening soil model

It is an advanced model to model the behavior of various types of soils, including both hard and soft soils, and employed by various researchers for the stability analysis of retaining structures (Shehata, 2016 and Rouille et al., 2005). Soil shows reduced stiffness and irreversible strains when subjected to high primary deviatoric stress. The main principle of this model is that, in a special case of drained triaxial test, the stress-strain relationship can be assessed by a hyperbola connecting elastic and plastic phase. The described relation can be seen in Figure 2.11 below.

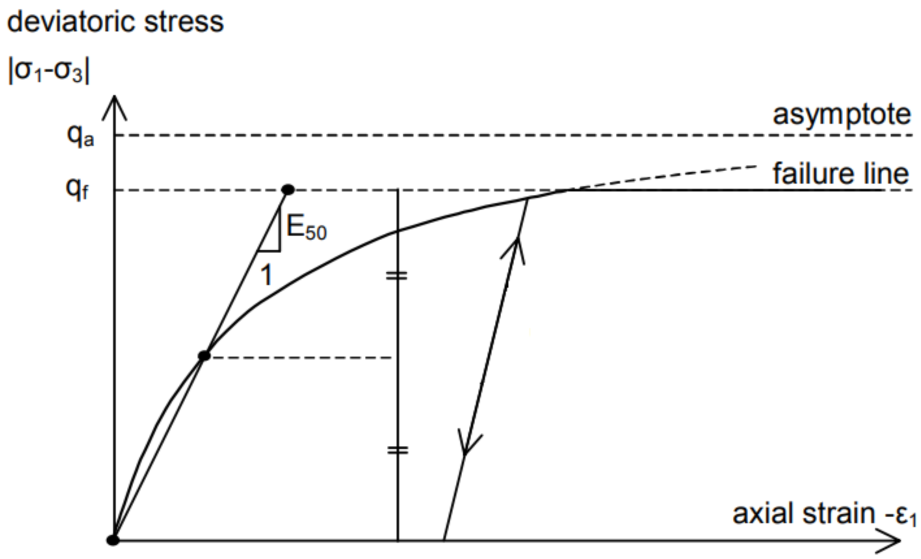


Figure 2.11. Hyperbolic stress-strain relationship (Soil hardening model)

The table illustrates the parameters required for the hardening soil model, which includes some of the Mohr-Coulomb soil model (c, Ø, and ψ).

Table 2.2. Hardening soil model parameters

S. No	Name	Symbol	Unit
1	Secant stiffness	E_{50}^{ref}	kN/m^2
2	Tangent stiffness	E_{oed}^{ref}	kN/m^2
3	Cohesion	c	kN/m^2
5	Friction angle	Ø	Degrees
6	Dilatancy angle	ψ	Degrees

2.6.4.1.5.1. Secant stiffness (E_{50}^{ref})

It is the stiffness value, which is estimated from standard drained triaxial test and has the which has a similar value as that used for the Mohr-Coulomb. Standard drained triaxial test tends to yield curves that can be described by:

$$-\varepsilon_1 = \frac{1}{2E_{50}} \frac{q}{1 - \frac{q}{q_a}} \text{ for } q < q_f \qquad \text{(Eq - 27)}$$

Where q_a is the asymptotic value of the shear strength and the parameter E_{50} is defined as

$$E_{50} = E_{50}^{ref} \left(\frac{c \cos\varnothing - \sigma_3' \sin\varnothing}{c \cos\varnothing + p^{ref} \sin\varnothing} \right)^m \qquad \text{(Eq - 28)}$$

where p^{ref} is the reference pressure, which by default is set to 100 kPa. Power m is the amount of stress dependency. The quantity q_a is given by

$$q_a = \frac{q_f}{R_f} \qquad \text{(Eq - 29)}$$

Where R_f is the failure ratio, which by default is set to 0,9 and the ultimate deviatoric stress, q_f is defined as,

$$q_f = \left(c \cot\varnothing - \sigma_3' \right) \frac{2 \sin\varnothing}{1 - \sin\varnothing} \qquad \text{(Eq - 30)}$$

2.6.4.1.5.2. Tangent stiffness (E_{oed}^{ref})

It is the tangent stiffness for primary oedometer loading (Carlstedt, 2008), and is calculated in the same way and E_{50}.

$$E_{oed} = E_{oed}^{ref} \left(\frac{c \cos\varnothing - \sigma_3' \sin\varnothing}{c \cos\varnothing + p^{ref} \sin\varnothing} \right)^m \qquad \text{(Eq - 31)}$$

Where p^{ref} and m are already defined in the above section.

2.6.4.2. Modeling of retaining wall and relief shelves

Plate elements in Plaxis represent structural members, like a beam, wall, or a slab, and therefore a bending stiffness (EI) and an axial stiffness (EA) must be included. So, the retaining wall is modeled using plate elements similar to the models of Shehata (2016), Yang and Liu (2007), and Huggins and Ravichandran (2011). Similarly, relief shelves are modeled the same way as that of retaining wall using plate elements. They are connected directly to the wall using a rigid connection. In Plaxis, when two plate elements are connected directly, the default connection is rigid (Brinkgreve et al., 2004). Plates with interfaces may be used to execute a representative and realistic analysis of geotechnical structures. The following are the parameters used to define a plate element.

Table 2.3. Material parameters for plate elements

Parameter	Name	Unit
Axial stiffness	EA	kN/m
Bending stiffness	EI	kNm^2/m
Unit weight	w	kN/m/m
Poisson ratio	υ	-

2.6.4.2.1. Axial stiffness (EA)

It is the resistance offered by a structural element against deformation in any particular axis. Factors affecting axial stiffness are thickness (d) and elastic properties (E) of the plate element.

$$EA = E\, d \qquad \text{(Eq - 32)}$$

2.6.4.2.2. Bending stiffness (EI)

It represents a force couple required to bend a structure in one unit of bending or the resistance offered by a structural element while experiencing some bending. It too depends upon the elastic properties (E) and thickness (d) of the plate element, and given by,

$$EI = \frac{E\, d^3}{12} \qquad \text{(Eq - 33)}$$

2.6.4.2.3. Unit weight (w)

It's obtained by multiplying the thickness of the plate element with its unit weight. Therefore, it has units of force per unit area. The weight of the plate element is not the full weight of the structures, but it is the weight of the structures minus the weight of removed soil (Figure 2.12).

2.6.4.2.4. Thickness (d)

In Plaxis thickness of the plate element is adjusted automatically by changing the magnitudes of bending and axial stiffnesses of the plate element using eq - 34. The characteristics of the plate element's thickness for both unexcavated and excavated cases are illustrated in Figures 2.11 (a) and (b), respectively.

$$d = \sqrt{\frac{12\ EI}{EA}} \qquad \text{(Eq - 34)}$$

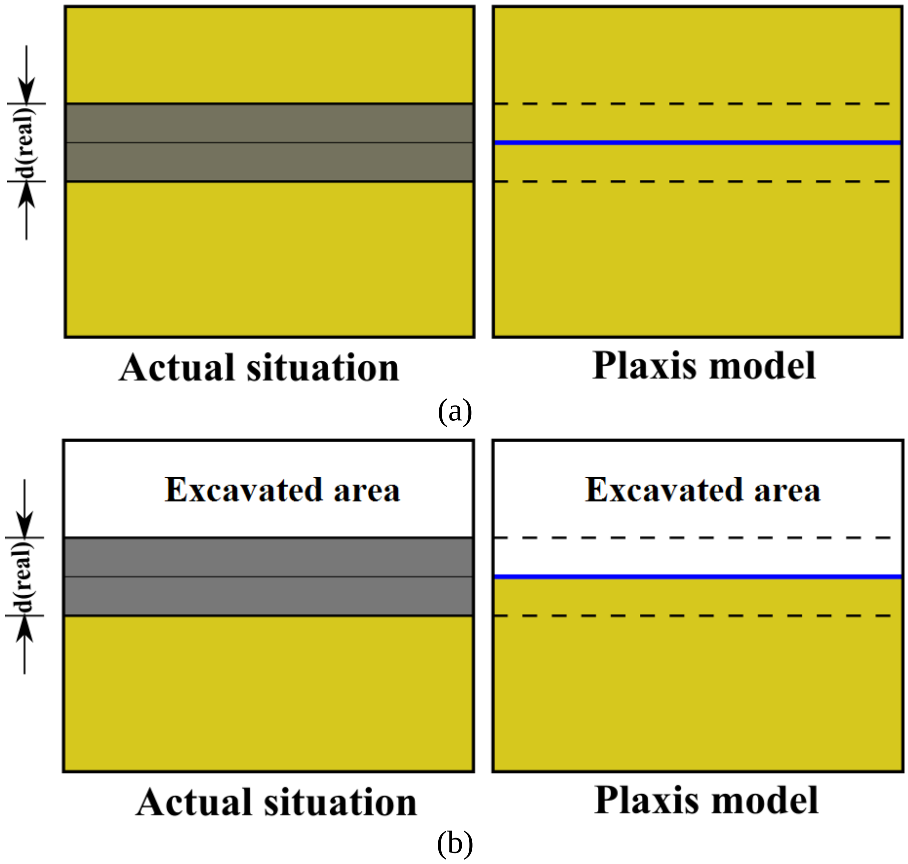


Figure 2.12. Comparison between the real situation with the Plaxis model for (a). wall within the soil and (b). wall with excavated soil

For the case in which plate is within the soil (Figure 2.11 (a)),

$$W_{real} = \gamma_{concrete} \, . \, d_{real} \qquad \text{(Eq - 35)}$$

$$W_{model} = \gamma_{soil} . \, d_{real} + W_{plate} \qquad \text{(Eq - 36)}$$

$$W_{model} = W_{real} \Rightarrow W_{plate} = \left(\gamma_{concrete} - \gamma_{soil}\right) . \, d_{real} \qquad \text{(Eq - 37)}$$

And for the case in which soil is not present on one side as in case of retaining wall (Figure 2.12 (b)),

$$W_{real} = \gamma_{concrete} \, . \, d_{real} \qquad \text{(Eq - 35)}$$

$$W_{model} = \gamma_{soil} . \, \frac{1}{2} d_{real} + W_{plate} \qquad \text{(Eq - 38)}$$

$$W_{model} = W_{real} \Rightarrow W_{plate} = \left(\gamma_{concrete} - \frac{1}{2}\gamma_{soil}\right) . \, d_{real} \qquad \text{(Eq - 39)}$$

2.6.4.2.5. Poisson ratio (ʋ)

It is the ratio between lateral strain and vertical strain in the direction of applied force. It is related to bulk modulus (K), shear modulus (G), and Young's modulus (Y), by following,

$$\upsilon = \frac{(3K - 2G)}{(6K + 2G)} \quad \text{(Eq - 40)}$$

$$E = 2\,G\,(1 + v) \quad \text{(Eq - 41)}$$

$$E = 3\,K\,(1 - 2v) \quad \text{(Eq - 42)}$$

2.6.4.3. Modeling interfaces

To simulate soil-structure interaction, interface elements between the soil and structures are used wherever both are in direct contact. The interface has a value ranging from 0 to 1, with 1 being the rigid connection and the values less than 1 indicate the less rigid connections. Some of the suggested values are given below.

Table 2.4. Suggested interface values

S. No	Interaction type	R_{int} value
1	Sand and Steel	0.6 – 0.7
2	Clay and steel	0.5
3	Sand and concrete	0.8 – 1.0
4	Clay and concrete	0.7 – 1.0
5	Soil and Geogrid (grouted body)	1.0
6	Soil and Geotextile	0.5 – 0.9

2.6.4.4. Meshing

After the creation of geometry model, and assignment of all the properties to all the closed polygons and plate elements representing soil and structural elements, respectively, the geometry has to be divided into small elements before the calculation stage. An arrangement of these small finite elements is called a mesh. Two types of meshes are, i). 15 nodded triangular element and ii). 6 nodded triangular elements. A fully automatic mesh of finite elements is generated in Plaxis by the triangulation method. Different aspects of mesh function in the Plaxis are discussed below.

2.6.4.4.1. Global coarseness

Five different levels of global coarseness have been defined, which is very coarse, coarse, medium, fine, very fine. The number and average size of elements of the generated mesh elements depend upon this setting for global coarseness. An estimate of the element's size (s) and numbers (n) are given below (before any local refinement).

i. Very coarse: [s = 25, n = 50]

ii. Coarse: [s = 50, n = 100]

iii. Medium: [s = 100, n = 250]

iv. Fine: [s = 200, n = 500]

v. Very fine: [s = 400, n = 800]

2.6.4.4.2. 15 & 6 Nodded triangles

The user has the choice to use either 6 of 15 nodded triangular elements (Figure 2.13) to analyze volume clusters like soil layers. Plaxis offers an interpolation of fourth and second order for the calculations of displacements, for 15 and 6 nodded elements, respectively. Therefore, the numerical integration includes twelve (12) and three (3) stress points for 15 and 6 nodded elements, respectively.

The 15 nodded triangle is comparatively precise that generates stress results of high quality for the problems. The use of 15 nodded triangles consumes comparatively higher memory with slower performance, regarding calculation and operation time. On the other hand, a relatively quick 6 nodded triangle is available that produces good results in standard deformation analyses if an adequate number of elements are used. However, for axisymmetric models or in situations when failure is a governing criterion, care should be taken while choosing this triangulation, such as a bearing capacity calculation by phi-c reduction. One 15 nodded element can be supposed as a combination of four 6 nodded elements, because the nodes and stress points would then be equal in quantity. Despite this, one 15 nodded elements are always more powerful and accurate than four 6 nodded elements. Therefore, in the present analysis 15 nodded mesh is being used along with some refinement.

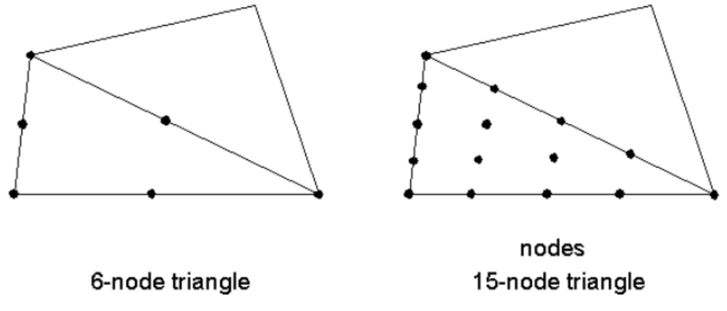


Figure 2.13. Position of nodes and stress points in soil element

2.6.4.4.3. Global refinement

This option is used to globally define a generated mesh from the submenu of mesh. When global refinement is used, the parameter of global coarseness is enhanced one level further (for instance from medium to fine).

2.6.4.4.4. Local coarseness

In a geometry when it is expected to have high-stress concentrations or large deformations at certain regions, then it is sometimes necessary to have finer mesh at those regions, while other regions unaffected. Such a situation mostly takes place when the model includes corners, edges, or structural members. For this purpose, Plaxis includes an additional local coarseness function for the parameter of global coarseness. The size factor of the local element is set as 1.0, by default. In the present study, local coarseness is used at regions where soil interacts with a structural element, e.g. stem and backfill and base slab and foundation.

2.6.5. Calculation methods and output

The calculation program of the Plaxis allows users to carry out the analysis in various ways depending upon the situation to be modeled. First, it is decided to select the type of calculation to be performed. The calculation type of each phase can be defined in the general tab of the calculation window, which are "plastic analysis", "consolidation analysis", "phi-c analysis", and "dynamic analysis". Then, some control parameters are to be defined, whether to use them or not. These parameters can be found and used inside the parameter tab of calculation window, which are "reset displacement to zero", "ignore undrained behavior", and "delete intermediate steps". Finally, type of loading is defined, which depends upon the situation to be rendered. Plaxis allows user to choose between three different types of loading input for a particular type of situation, which are "staged construction", 'total multiplier", and 'incremental loading". After calculation stage is completed, output program is opened to extract the results required for the analysis, like stresses and deformations, etc.

Chapter. 3

3. METHODOLOGY & RESEARCH WORK

3.1. Introduction

The purpose of this chapter is to describe the procedure of carrying out the analysis using finite element modeling by Plaxis 2D, which is being used by the professionals worldwide for the problems related to geomaterials. It will include the data set for several materials used for the purpose of present analysis. Moreover, for studying the effectiveness of relief shelves on the stability of retaining wall, many models will be analyzed that will be used to observe the effect of these parameters on various outcomes related to wall's stability.

3.2 Geometric configuration of the model

A geotechnical problem under consideration is rendered using a geometrical model, which requires creating soil bodies in the form of clusters or closed polygons using a number of lines, and structural elements like beams and walls using plate elements, along with some necessary boundary conditions, etc. As stability analyses of retaining wall models are to be carried out in the present study, the geometrical model will include backfill, foundation, and a retaining wall. For the selection of dimensions of the geometrical model for the present study, the numerical models studied by Shehata (2016), Chauhan and Dasaka (2018), and Ayuluri and Ramulu (2017), etc. are considered, and a geometrical model is developed, with dimensions of backfill, foundation and retaining wall, which are illustrated in the table 3.1.

Table 3.1. Finite element model for present study

S. 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	-

Furthermore, three different categories of retaining wall are modeled depending upon the number of relief shelves attached. The three categories are retaining wall without relief shelf, retaining wall with single relief shelf, and retaining wall with two relief shelves. For the walls with shelves, a number of models are made by varying the dimensions of relief shelves. These parameters are width factor, location factor, and thickness, and are defined below.

i. Width factor (w) $= \dfrac{\text{Width of relief shelf (b)}}{\text{Height of retaining wall (H)}}$

ii. Location factor (L) $= \dfrac{\text{Distance from the top of wall to relief shelf (h)}}{\text{Height of retaining wall (H)}}$

iii. Thickness (t)

A pictorial view of the retaining wall model is presented in the Figure 3.1 below, including relief shelves and related parameters to be studied. The backfill width to wall height ratio used in the literature is between 1 to 4 (Shehata, 2016, Chauhan and Dasaka, 2018, and Ayuluri and Ramulu, 2017), so, in the present study 3 is used. Moreover, in the model, a line originating from the heel of the footing at an angle of 45^0(Figure 3.1) is made for the purpose of excavation, according to the repose angle of soil (Al-Hashemi et al, 2018). Also, in the model, the interface elements are applied at the regions where structural elements interact with soil body, which can be seen with dotted lines along the retaining wall in Figure 3.1.

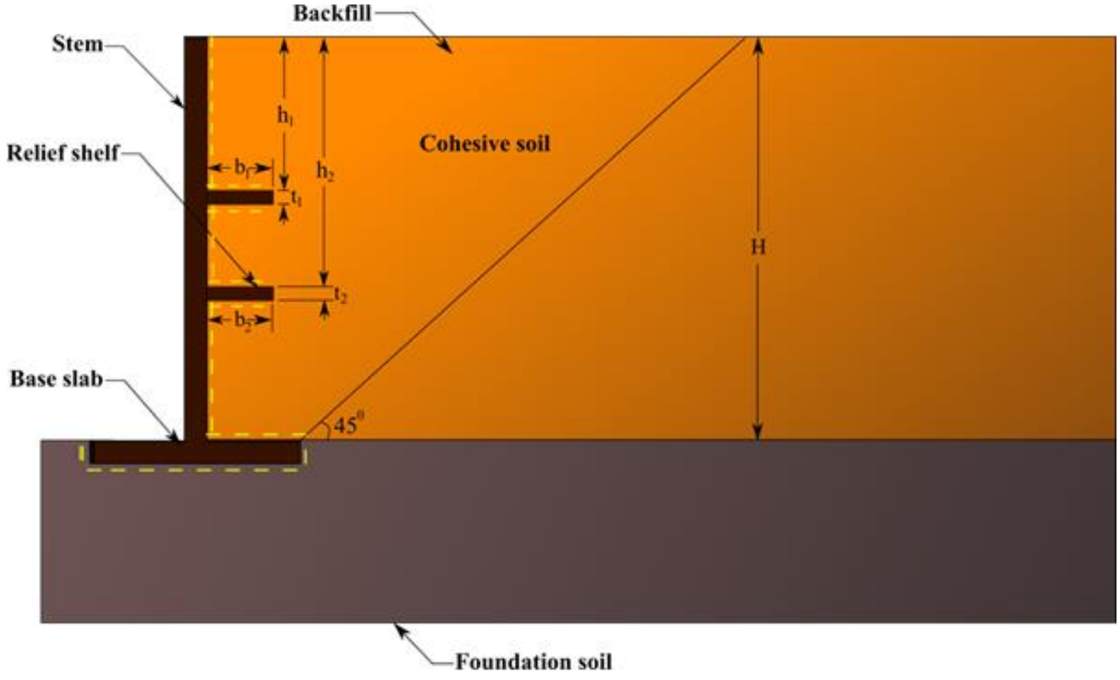


Figure 3.1. Model of retaining wall with relief shelves used in the study

3.3. Material set properties of backfill and retaining wall

After creating the geometrical model using points, lines, and plate elements, material set properties are assigned to the respective clusters and plate elements. The material properties of the backfill, foundation, and retaining wall are discussed below.

3.3.1. Backfill and foundation

Mohr Coulomb's elastic perfectly plastic soil model is used to model the backfill and foundation soils to simulate the behavior of relief shelves supported retaining walls. For backfill, a silty clay of Sohbat Charra, district Battagram, Pakistan is selected, and the materials' properties as reported by Khan et al. (2014) of this soil is used in the analysis. Moreover, interface elements are used to model soil-structure interaction by specifying a number from 0 to 1 (1 being the rigid connection). The interface as suggested by Dennis (2006) are used. Furthermore, dense sand is used in the foundation/base of the retaining wall and the values as suggested by Shehata (2016) is selected for the model. Table 3.2 and Table 3.3 illustrates the soil properties of backfill and foundation soils used in the model respectively.

Table 3.2. Backfill soil properties

S. No	Property/parameters	Estimated Value	Unit
1	Unit weight	17.04	kN/m^3
2	Angle of Internal friction	36.30	Degrees
3	Cohesion	8.10	kN/m^2
4	Dilatancy angle	0	Degrees
5	Modulus of elasticity	10,000	kN/m^2
6	Poisson ratio	0.265	-
7	Interface value	0.8	-

Table 3.3. Foundation soil material properties

S. No	Property	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	50,000	kN/m^2
6	Poisson ratio	0.3	-
7	Interface value	1.0	-

3.3.2. Retaining wall and relief shelves

Retaining wall and relief shelves are modeled using plate elements, with the properties of reinforced concrete as described by Standard (2011), Kulkarni (2012), and Brooks (2014). Plate elements are used in Plaxis for the modeling of structural elements using a linear elastic model. The parameters required for the linear elastic model are flexural rigidity (EI), axial rigidity (EA), unit weight per unit length (w), and Poisson ratio (υ); where EA and EI depend upon elastic modulus of the material and thickness of the structure, which can be estimated using equations no. 27 and 28, respectively (Dennis, 2006). Table 3.4 illustrates the properties of the retaining wall.

$$EA = E\,d \qquad \text{(Eq - 27)}$$

$$EI = \frac{E\,d^3}{12} \qquad \text{(Eq - 28)}$$

Table 3.4. Material properties of retaining wall's stem and footing

S. No	Properties	Stem	Footing	Unit	References
1	Modulus of elasticity (E)	30,000,000	30,000,000	kN/m^2	Kulkarni (2012)
2	Flexural rigidity (EI)	3,125,000	857,500	kNm/m	Dennis (2006)
3	Axial rigidity (EA)	15,000,000	21,000,000	kN/m	Dennis (2016)
4	Unit weight per length (w)	12.5	17.5	kN/m^2	Standard (2011)
5	Poison ratio (υ)	0.15	0.15	-	Brooks (2014)

After specifying the properties of backfill, foundation soil, retaining wall stem, and retaining wall footing, each of them is applied to their respective clusters and plate elements.

3.3.3. Boundary conditions

Boundary conditions for the present study are listed below.

i. Total fixities are applied to the bottom-most boundary of the model, while horizontal fixity to both right and left most vertical boundaries of the model (Guler et al., 2007 and Mecevski, 2015). Applying a fixity to a plane or line in the model means to set its prescribed displacement to zero; so that the plane cannot move in a certain direction (horizontal, vertical, or both). It is an important feature of Plaxis modeling, as without setting it, meshing and further calculations cannot be done.

ii. The backfill is horizontal.

iii. The non-yielding retaining wall is being modeled, which means that it is not anchored at the top to restrict any movement and can freely deflect away from the backfill.

iv. For the present study, the groundwater table is not considered for the analysis.

3.3.4. Type of meshing

After assigning the defined material properties to all the clusters and structural elements, the mesh is generated by entering into a mesh generation setting, which will require the user to select the type of mesh to be generated, already explained in the section 2.6.4.4. of chapter 2. After that, further refinement of the mesh can be done for certain selected regions. For the present study, first, a “fine” mesh is used for complete geometry. Then, “refine cluster” meshing of the backfill material to be excavated and backfilled in the calculation stage is used. This will not only produce higher quality results along with saving the time, which could be wasted if the very fine mesh was to be used for the complete geometry. Similarly, the mesh consists of 15 nodded triangular elements, because it produces higher quality stress and deformation results, as a larger number of stress points are present in it as compared to 6 nodded triangular elements.

3.4. Method of analysis

For the present study, plastic analysis is used, which is used for most of the geotechnical situations, in which elastoplastic analysis is carried out, and the original geometry before deformation forms the basis for the calculation of stiffness matrix. For the present study, backfill soil is modeled as an undrained material, as cohesive soils tend to have undrained behavior mostly. On the other hand, foundation soil, which is dense sand, is modeled a drained material because of the presence of sand which is usually in drained condition.

3.4.1. Calculation control parameters

Plaxis requires the user to specify either use of some control parameters in calculation phases is required or not, which will influence the estimation of stresses and displacements within a certain phase. These control parameters are reset displacement to zero, ignore undrained behavior, and delete intermediate steps.

3.4.1.1. Reset displacement to zero

When the irrelevant displacement of the previous phase is not to be taken into account in the current phase, such as displacements due to gravity, then this option has to be checked in the current phase. On the other hand, if this option is not checked, then the deformations of the previous phase will be added to the next phase, however, it does not affect the stress field. For the present analysis, this option is not used.

3.4.1.2. Ignore undrained behavior

When an undrained material is used in the analysis, but for the time being the user wants undrained behavior of the material to be ignored, such as sometimes, due to gravity loading unrealistic pore pressures may be produced, which is not usually considered for long term analysis; then this option has to be checked. So, this option will enable the user to conduct an undrained analysis during main loading stages, and drained analysis during gravity loading. For the present study, this option is kept unchecked.

3.4.1.3. Delete intermediate steps

In order to save disk space, the additional intermediate output steps are by default deleted, and only the relevant outputs are kept, and less important ones are deleted. Considering this, this option is checked in the calculation phases.

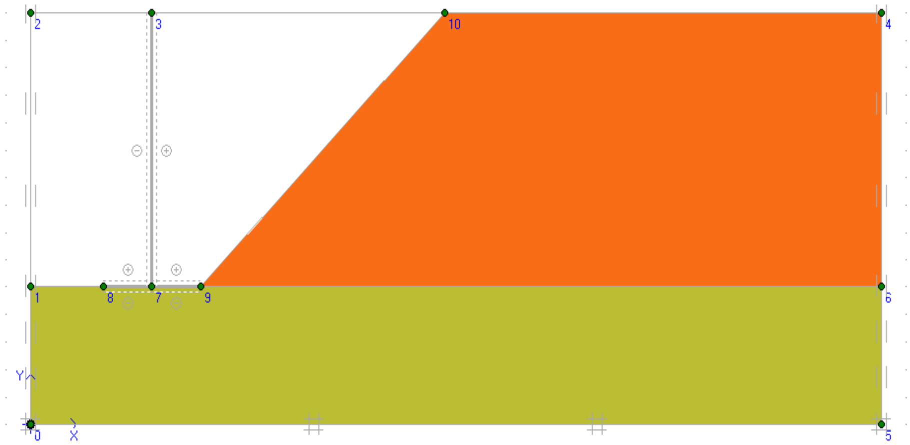
3.4.2. Loading input

Among the three different types of loading input, one of them has to be used to simulate the loading situations for the problem under consideration. These input types are staged construction, total multiplier, and incremental loading. For the present analysis, which includes the construction of a retaining wall, staged construction is used to simulate the actual process of wall construction. This feature enables the user to simulate real-time construction procedures like excavation, backfilling, and updated parameters, etc., by activating and deactivation of the clusters and plate elements, changing water tables and updating loading and displacements, etc. For the present study, all the models were constructed in three stages listed below.

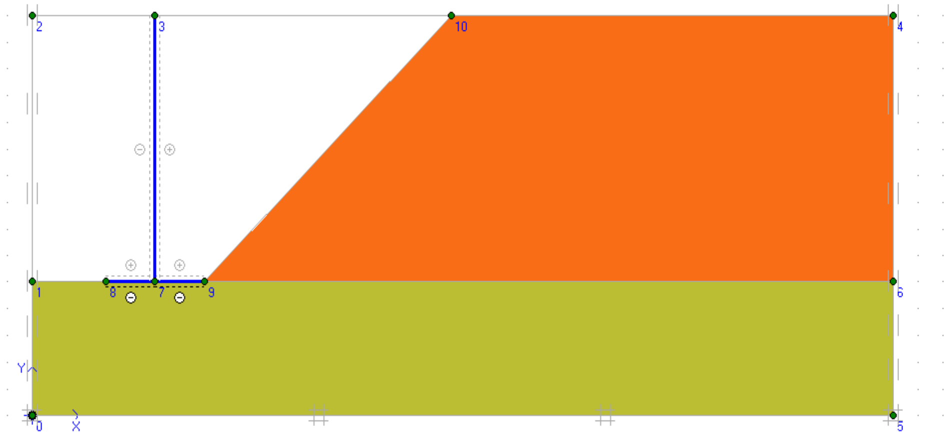
i. Excavation of soil at an angle of 45^0 considering the material's repose angle by deactivating the cluster in the backfill (Figure 3.2 (a)).

ii. Construction of the retaining wall, by activating the plate elements (Figure 3.2 (b)).

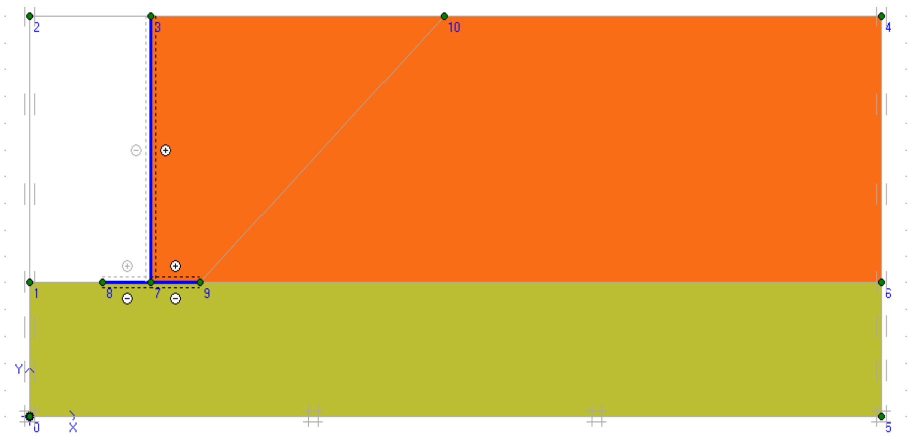
iii. Backfill the same material previously excavated, by activating back the deactivated cluster (Figure 3.2 (c)).



(a)



(b)

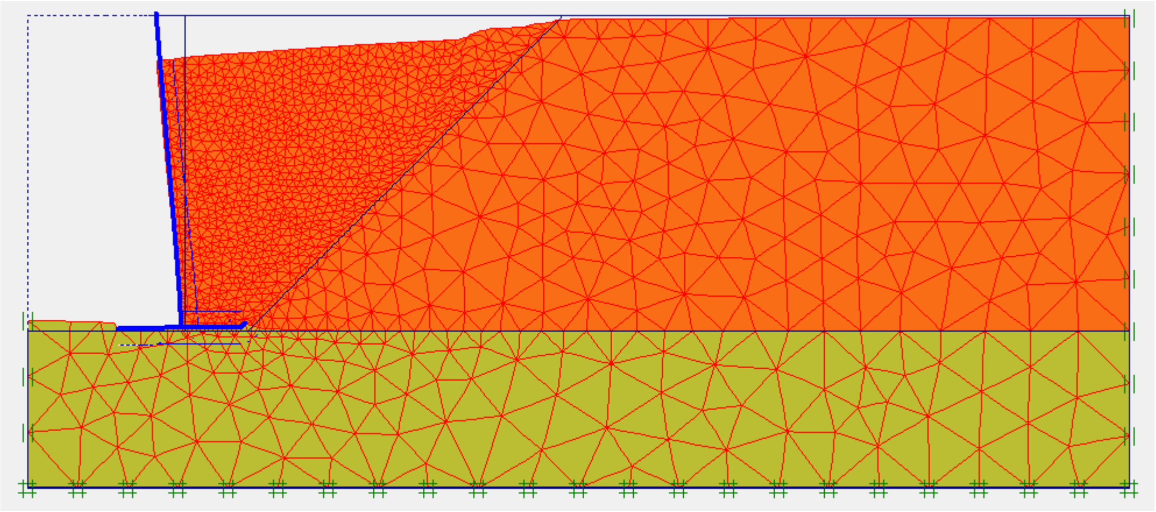


(c)

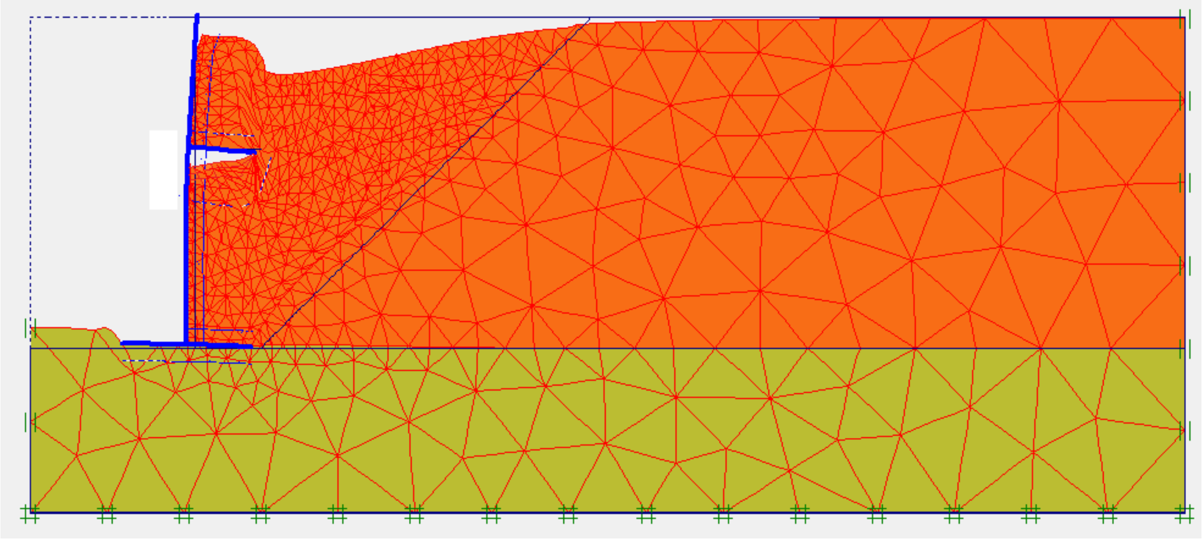
Figure 3.2. Construction stages of (a). excavation, (b). wall construction, and (c). backfilling

3.5. Output and results to be analyzed

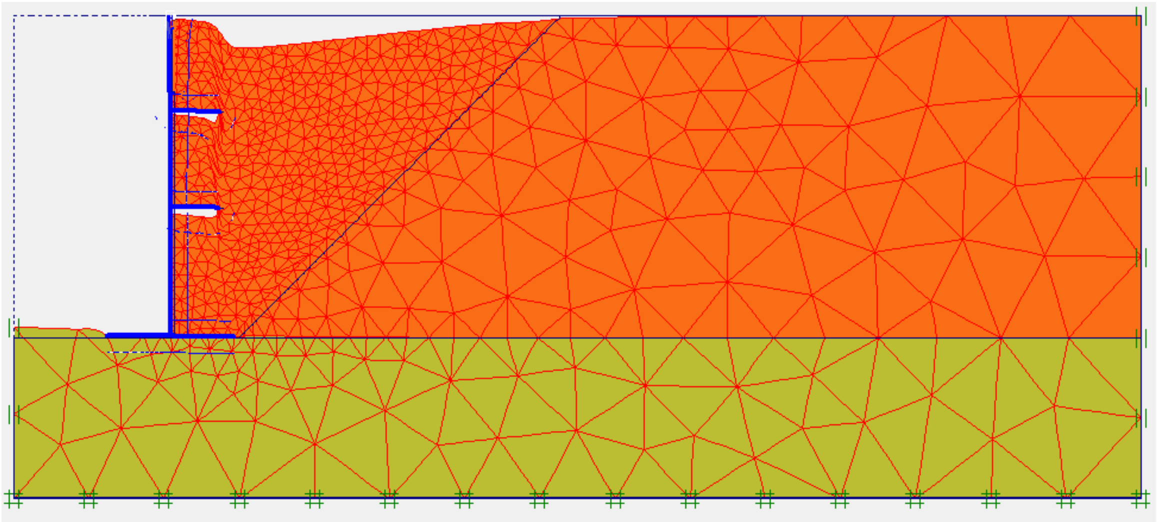
After the calculation stage, there is an output program, which will show the exaggerated deformed shape of the model with some suitable scale factor, e.g. 25 for the present case, so that the situation after the application of loads can be realized clearly (Figure 3.3 (a, b, and c)).



(a)



(b)



(c)

Figure 3.3. Deformed shape with a scale factor of 25 for retaining wall (a). without relief shelf, (b). with a single relief shelf, and (c). with two relief shelves

Upon completion of analyses, the results extracted from the analysis to assess the stability of the retaining wall are listed in Table 3.5 below.

Table 3.5. Outcomes of the analyses

S. No	Result	Symbol	Unit
1	Active earth pressure	P_a	kN/m^2
2	Total lateral thrust	P	kN/m
3	Shear stress on wall stem	S	kN/m^2
4	Bending moment	M	kNm
5	Wall top movement	D_T	m
6	Base sliding	D_s	m
7	Factor of safety against sliding	$FOS_{(Sliding)}$	-
8	Factor of safety against overturning	$FOS_{(Overturning)}$	-

3.6. Finite element models for the present study

To conduct a parametric study to analyze and observe the effect of various parameters of relief shelves such as width, thickness, location on the wall, and their number on the distribution of lateral active earth pressure (P_a), total lateral thrust (P), bending moment (M), shear stress (S), overturning movement at the top (D_T), sliding (D_S) at the base of the wall, and finally factor of safety against sliding ($FOS_{Sliding}$) and overturning ($FOS_{Overturning}$) for the cases with optimum dimensions of relief shelves, several different models are required to be made with different dimensions of relief shelves. For this purpose, the models are broadly classified as retaining wall with a single relief shelf and retaining wall with two relief shelves. Within each case, dimensions of the parameters of relief shelf such as location, width, and thickness are varied to examine their effect on the stability of retaining wall, by interpreting the results illustrated in Table 3.5. Moreover, the results of retaining wall without, with one and two shelves will also be compared to observe the effect of the number of shelves on the stability of the wall. A brief description of the methodology given in Table 3.8.

3.6.1. Retaining wall with single relief shelf

In this category, a total of 27 analyses are performed by varying three parameters (described in section 3.2) of the only relief shelf and observing their effect on the stability of retaining wall. It is further classified into three categories based on the particular parameter to be varied while keeping constant the other two parameters. Table 3.6 illustrates the dimensions of the single relief shelf's parameters varied among different models.

Table 3.6. Models for retaining wall with single relief shelf

S. No	Parameters	Models						Total
1	Width factor (w)	L = 0.2, 0.4, 0.6, 0.8, and t = 0.5m						27
		0.05	0.1	0.15	0.2	-		
2	Location factor (L)	w = 0.05, 0.1, 0.15, 0.20, and t = 0.5m						
		0.2	0.3	0.4	0.5	0.6	0.8	
3	Thickness (t)	L = 0.4 & w = 0.15						
		0.2m	0.3m	0.4m	0.5m	-		

3.6.1.1. Width

In this category, a total of sixteen (16) analyses are performed with four sub-groups. In each of the sub-group, location factor and thickness (0.5 m) of the shelf are kept constant and width factor (w_1) is varied from 0.05 to 0.20. The shelves are attached one by one at different location factors of 0.2, 0.4, 0.6, and 0.8, and width factors are varied as follows.

i. w_1 = 0.5 m /10 m = 0.05

ii. w_1 = 1.0 m /10 m = 0.10

iii. w_1 = 1.5 m /10 m = 0.15

iv. w_1 = 2.0 m /10 m = 0.20

3.6.1.2. Location

In this category, collectively 24 analyses are performed with four sub-groups. Within each of the sub-group, width factor and thickness of 0.5m of the shelf are kept constant and location factor (L_1) is varied from 0.2 to 0.8. The sub-groups have the width factors of 0.05, 0.10, 0.15, and 0.20, with the same thickness of 500mm, and the location factor is varied as follows.

i. L_1 = 2 m /10 m = 0.2

ii. L_1 = 3 m /10 m = 0.3

iii. L_1 = 4 m /10 m = 0.4

iv. L_1 = 5 m /10 m = 0.5

v. L_1 = 6 m /10 m = 0.6

vi. L_1 = 8 m /10 m = 0.8

3.6.1.3. Thickness

In this category, collectively 4modelsare made and analyzed by varying thickness (t_1) of the relief shelf and keeping constant the width factor and location factor of 0.15 and 0.4, respectively, which are as follows.

i. t_1= 0.2m

ii. t_1 = 0.3m

iii. t_1 = 0.4m

iv. t_1 = 0.5m

3.6.2. Retaining wall with two relief shelves

In this category, collectively30 analyses are performed to observe the behavior of retaining wall with two relief shelves, by varying each of the parameters in different combinations. Table 3.7 illustrates the dimensions of the two relief shelves' parameters varied among different models.

Table 3.7. Models for retaining wall with two relief shelves

S. No	Parameter	Models								Total
1	Width factor (w)	L = 0.2 - 0.4, 0.2 - 0.6, 0.4 - 0.6, and t = 0.5m								30
		0.05 0.05	0.10 0.05	0.2 0.05	0.05 0.10	0.05 0.20	0.10 0.10	- -		
2	Location factor (L)	w = 0.15 and t = 0.5m								
		0.2 0.4	0.2 0.6	0.2 0.8	0.6 0.4	0.3 0.6	0.3 0.4	0.3 0.5	0.3 0.7	
3	Thickness (t)	L = 0.2 - 0.4 and w = 0.15								
		0.2m 0.2m	0.3m 0.3m	0.4m 0.4m	0.5m 0.5m	- -				

3.6.2.1. Width

To study the influence width of both the shelves (b_1 for upper shelf and b_2 for lower shelf), thee sub-groups are made with distinction in location factors of the relief shelves, and same thickness of 0.5m. The three groups have the location factors of 0.2 and 0.4, 0.2 and 0.6, and 0.4 and 0.6, and the width factors of both the shelves are varied within each sub-group as follows.

i. $w_1 = 0.05$ and $w_2 = 0.05$
ii. $w_1 = 0.10$ and $w_2 = 0.05$
iii. $w_1 = 0.20$ and $w_2 = 0.05$
iv. $w_1 = 0.05$ and $w_2 = 0.10$
v. $w_1 = 0.05$ and $w_2 = 0.20$
vi. $w_1 = 0.10$ and $w_2 = 0.10$

3.6.2.2. Location

To observe the influence of the location of relief shelves (L_1 for upper shelf and L_2 for the lower shelf), nine different combinations of locations factors are carried out for width factor and thickness of 0.15 and 0.5m, respectively, of both the shelves, which are as follows.

i. $L_1 = 0.2$ and $L_2 = 0.4$
ii. $L_1 = 0.2$ and $L_2 = 0.6$

iii. L_1 =0.2 and L_2 = 0.8

iv. L_1 =0.4 and L_2 = 0.6

v. L_1=0.3 and L_2 = 0.5

vi. L_1 =0.3 and L_2 = 0.6

vii. L_1 =0.3 and L_2 = 0.4

viii. L_1 =0.3 and L_2 = 0.7

ix. L_1 =0.5 and L_2 = 0.6

3.6.2.3. Thickness

To observe the influence of thickness of the shelves (t_1 for upper shelf and t_2 for lower shelf), retaining wall with two shelves with location factors 0.2 and 0.4, and width factor 0.15, four different combinations of thicknesses are analyzed which are as follows,

i. t_1 = 0.2 m and t_2 = 0.2 m

ii. t_1 = 0.3 m and t_2 = 0.3 m

iii. t_1 = 0.4 m and t_2 = 0.4 m

iv. t_1 = 0.5 m and t_2 = 0.5 m

Table 3.8. Complete scheme of research methodology

S.N	Wall type	Parameters	Models								Analyses
1	Simple retaining wall	-	-								1
2	Retaining wall with single relief shelf	Width factor (w)	L = 0.2, 0.4, 0.6, 0.8, and t = 0.5m								27
			0.05	0.1	0.15	0.2	-	-			
		Location factor (L)	w = 0.05, 0.1, 0.15, 0.20, and t = 0.5m								
			0.2	0.3	0.4	0.5	0.6	0.8			
		Thickness (t)	L = 0.4 & w = 0.15								
			0.2m	0.3m	0.4m	0.5m	-	-			
3	Retaining wall with two relief shelves	Width factor (w)	L = 0.2 - 0.4, 0.2 - 0.6, 0.4 - 0.6, and t = 0.5m								30
			0.05 0.05	0.10 0.05	0.2 0.05	0.05 0.10	0.05 0.20	0.10 0.10	- -		
		Location factor (L)	w = 0.15 and t = 0.5m								
			0.2 0.4	0.2 0.6	0.2 0.8	0.6 0.4	0.3 0.6	0.3 0.4	0.3 0.5	0.3 0.7	
		Thickness (t)	L = 0.2 - 0.4 and w = 0.15								
			0.2m 0.2m	0.3m 0.3m	0.4m 0.4m	0.5m 0.5m	- -				
								Total			58

3.7. Summary

According to the methodology described in the above sections, 58 models are made and analyzed, and after carrying out the analysis and extracting the required results of active earth pressure, shear stress on wall stem, bending moment, wall top movement, and base sliding, the results are interpreted so that an understanding can be made regarding the effect of different parameters of relief shelves on the stability of retaining wall. From the interpretation of the results, optimum dimensions of the relief shelves in both the cases of single and two relief shelves can be found among all the models analyzed.

Chapter. 4

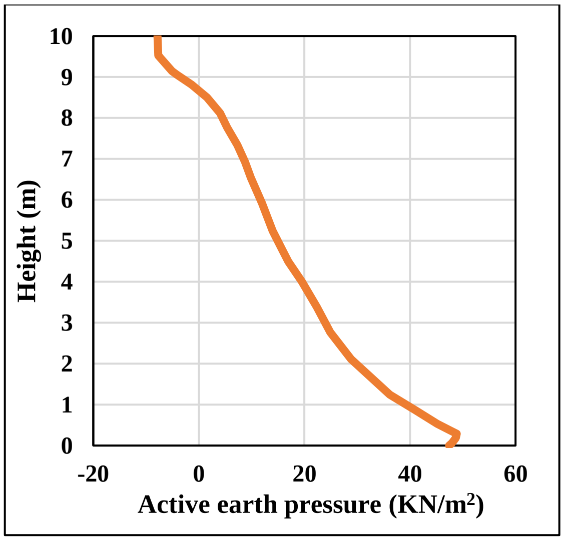
4. RESULTS & DISCUSSION

4.1. Introduction

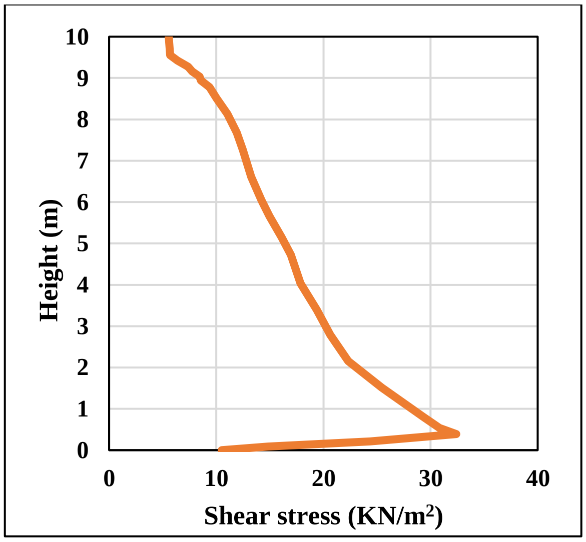
This chapter will include all the results obtained from the analyses done on 58 models while analyzing the influence of the parameters of relief shelves on the stability of the retaining wall. Separately, active earth pressure, bending moment, shear stress, wall top movement, and base sliding for different models analyzed will be discussed for each parameter to draw conclusions regarding the influence of their dimensions. In the end, optimum dimensions of relief shelves for both the categories of single and two relief shelves will be found among all the models analyzed.

4.2. Retaining wall without relief shelf

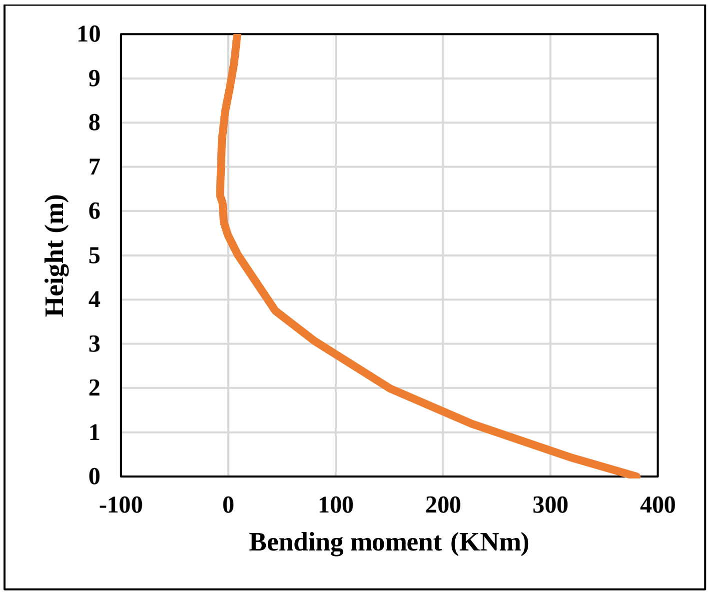
Simple cantilever retaining wall of height (H) was modeled first and analyzed for stability. Active earth pressure distribution, shear stress, base sliding, wall top movement, and overturning bending moment are analyzed and can be seen in Figure 4.1 below. The maximum active earth pressure (P_a) and total lateral thrust (P) on the wall by backfill are found to be 48.87 kN/m^2 and 176.17 kN/m, respectively, which produced a maximum overturning bending moment (M) of 380.21 kNm. Similarly, wall top movement (D_T) and base sliding (D_S) of the wall are found to be 0.01824 m and 0.00679 m, respectively.



(a)



(b)



(c)

Figure 4.1. Distribution of (a). active earth pressure, (b). shear stress, and (c). bending moment for simple cantilever retaining wall

4.3. Retaining wall with single relief shelf

Collectively 27 models were developed and analyzed to observe the behavior of retaining wall regarding its stability for a single relief shelf and to estimate the influence of width, location, and thickness of the relief shelf. Effectiveness of width, location, and thickness on the stability of retaining wall is discussed below by observing the results of active earth pressure, shear stress, wall top movement, base sliding, and bending moment along the wall.

4.3.1. Effect of shelf width factor

To analyze the effect of shelf width, a total of 16 models were constructed by keeping thickness constant at 0.5m and varying width factor (w) from 0.05 to 0.20 for different location factors (L) of 0.2, 0.4, 0.6, and 0.8.

4.3.1.1. Active earth pressure (P_a)

While analyzing active earth pressure distribution of retaining walls with relief shelf, it was found to be terminated at the location of the shelf, and started from the far end beneath the shelf, as if there was no soil above it (Figure 4.2). The shape of the distribution resembled the ones illustrated by Chougule (2017), Chauhan et al. (2016), and Shehata (2016), etc., except the tension part which was produced at the location of relief shelf due to the presence of cohesive backfill. Also, it was observed that, as the width factor was increased, the maximum value of active earth pressure and total lateral thrust on the wall as well as the lateral thrust on the wall was decreased, which can be seen in Figure 4.2 below. Similar types of results were obtained by Chauhan et al. (2016) and Shehata (2016).

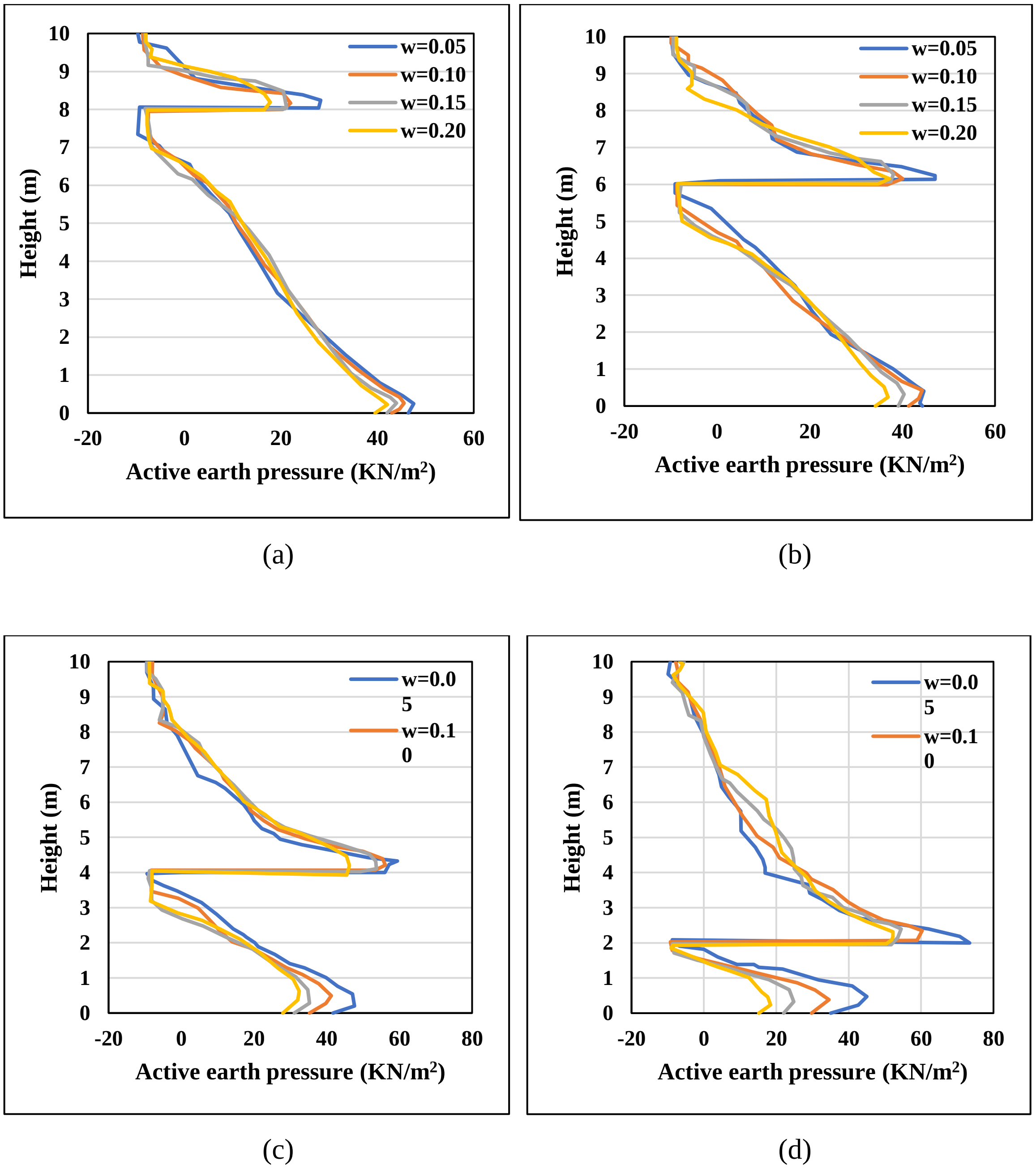
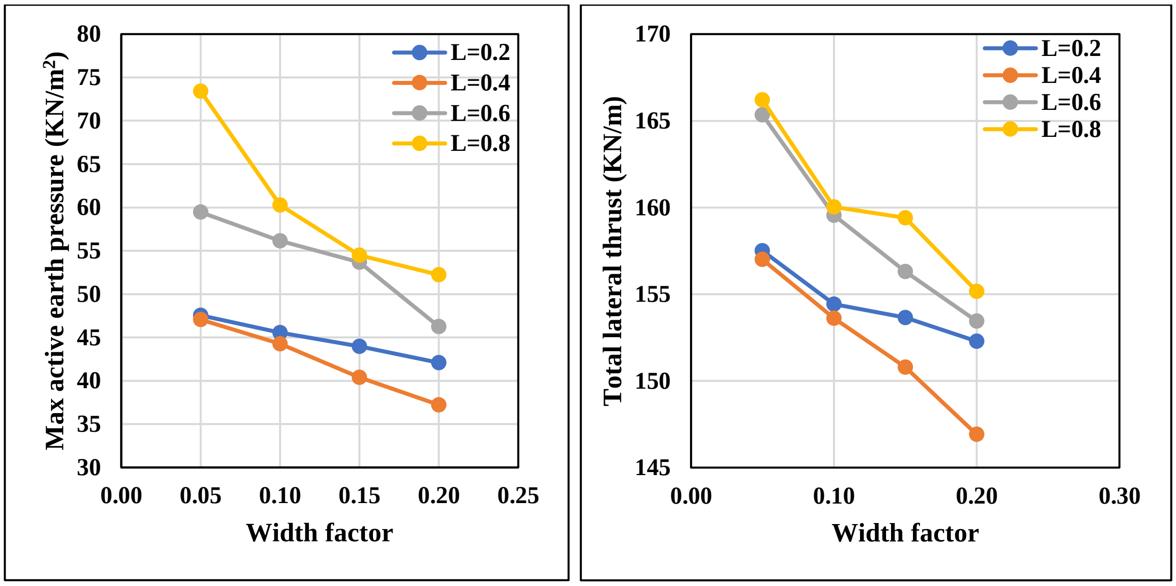


Figure 4.2. Active earth pressure distribution for location factor, (a). 0.2, (b). 0.4, (c). 0.6, and (d). 0.8, for single relief shelf



(a) (b)

Figure 4.3. Variation of (a). maximum active pressure and (b). lateral thrust on the wall with location factor, for single relief shelf

At the position of relief shelf, the active earth pressure surpassed the pressure at that point for a simple cantilever. But, ultimately the maximum value of earth pressure was reduced for most of the cases, while lateral thrust in all the cases was reduced (Figure 4.3). Maximum reduction up to 23.84 percent in maximum active earth pressure and 16.58 percent in lateral thrust were observed when location factor and width factor were 0.4 and 0.2, respectively.

4.3.1.2. Shear Stress (S)

While observing shear stress distribution on the retaining wall with shelf, it was found to be terminated at the location of the relief shelf and started from a lesser value beneath the shelf (Figure 4.4). Moreover, for all the cases as the width factor was increased by keeping location factor constant in a particular case, the reduction occurred in the maximum value of shear stress along the wall (see Figures 4.4 and 4.5). Shear stresses at the location of the shelf were found to be higher than that of a simple wall, which might be due to comparatively higher resultant active force on that portion of the wall (up to the location of the shelf). This lightens the importance of the design of the section at the junction of the stem and relief shelf. However, the shear stress reduced up to 21.79 percent for single relief shelve, considering the location factor and width factor of 0.4 and 0.2respectively, as compared to other scenarios.

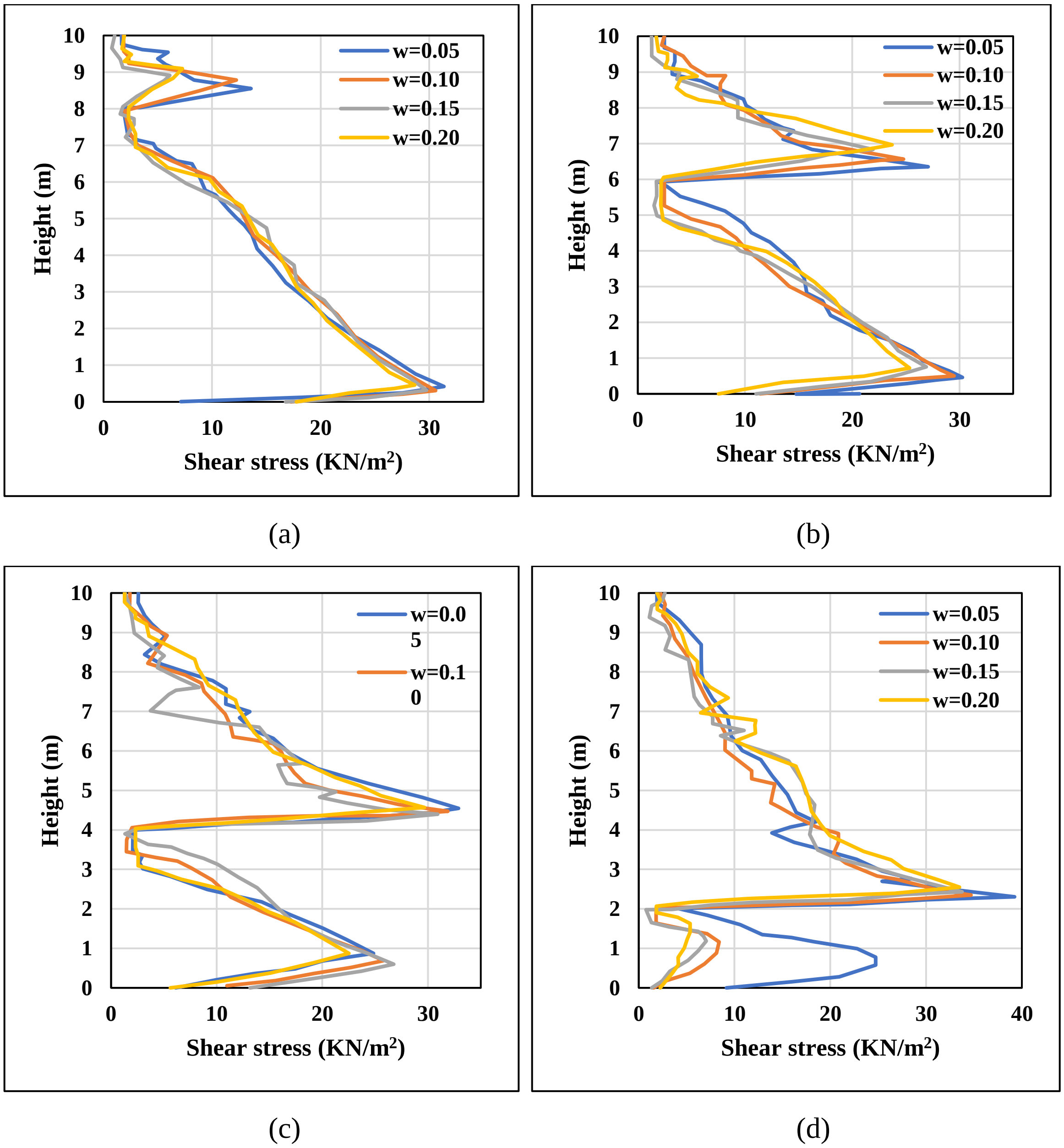


Figure 4.4. Shear stress along the wall for location factor, (a). 0.2, (b). 0.4, (c). 0.6, and (d). 0.8, for single relief shelf

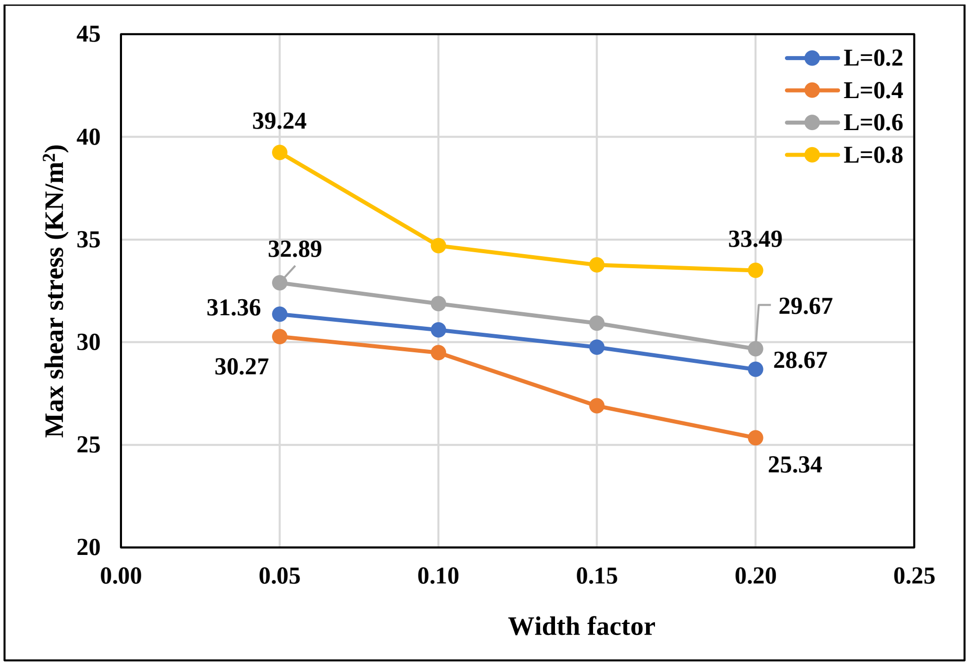
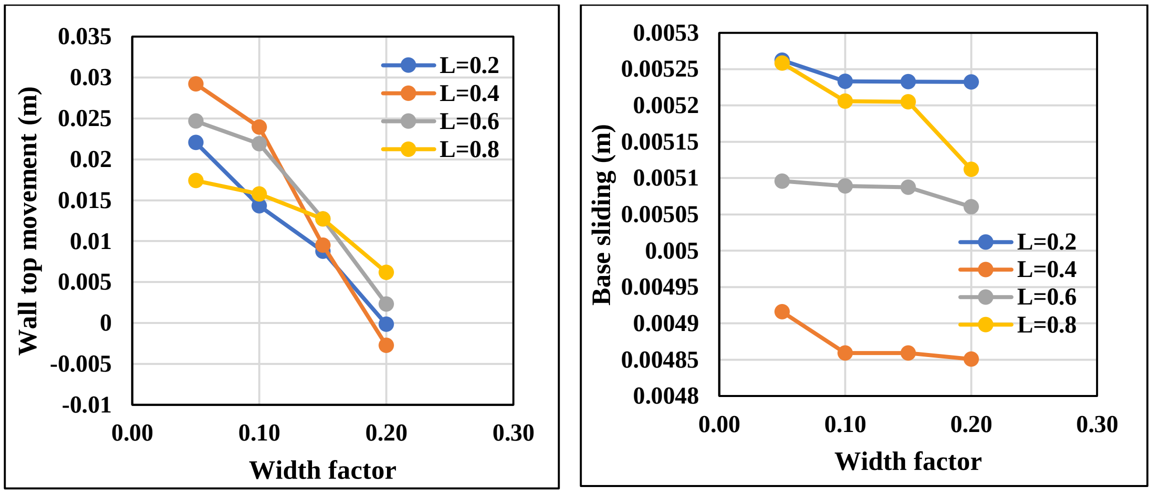


Figure 4.5. Variation of maximum shear stress along the wall with width factor, for single relief shelf

4.3.1.3. Wall top movement (D_T) and base sliding (D_S)

The top movement and base sliding of the wall reduced significantly with a gradual increase in the width factor from 0.05 to 0.20 of the relief shelf (Figure 4.6). For a width factor of 0.05, the wall top movement slightly increased as compared to a simple retaining wall. But as the width factor was increased further, the top wall movement started to reduce significantly (as shown in Figure 4.6). These results are in good agreement with the findings of Shehata (2016). Moreover, the wall top movement reduced from13.65 to 114.98%for width factor between 0.05 and 0.20. Similarly, Chougule (2017) reported that the wall top movement was reduced up to 50 % for a width factor of 0.35when a cohesionless soil was used as a backfill material. Similarly, the base sliding also reduced from 22.53 to 28.57percentwith a gradual increase in the width factor (Figure 4.6). However, the relief shelves supported wall provided minimum top wall movement of -0.00273 m (negative sign for movement towards the backfill) and base sliding of 0.00485 m with a width factor of 0.2 and location factor of 0.4 as compared to the simple retaining wall, where D_T and D_S were 0.01824 m and 0.00679 m, respectively.

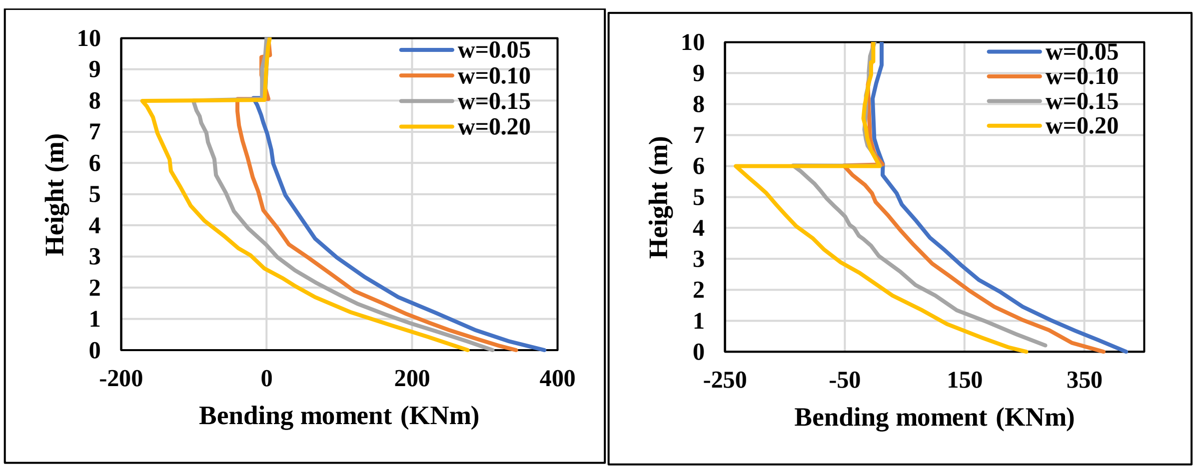


(a) (b)

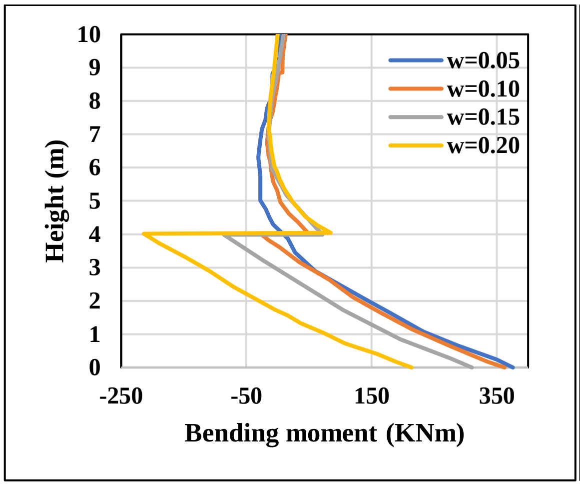
Figure 4.6. Variation of (a). wall top movement and (b). base sliding with width factor, for single relief shelf

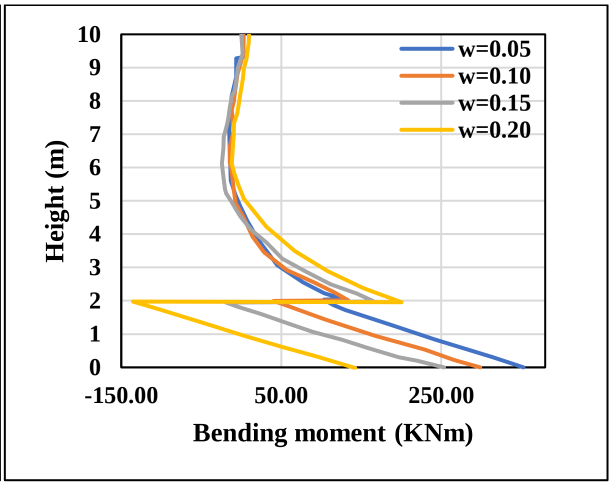
4.3.1.4. Bending moment (M)

Similar to top wall movement and base sliding (Figure 4.6), the introduction of the relief shelf reduced the overturning bending moment of the retaining wall significantly (Figure 4.7). From Figure 4.7, it can be seen that the positive bending moment responsible for the deflection of the wall away from the backfill, is reduced (up to 47.28 percent as compared to the wall without shelf) with the increase in width factor. Moreover, the negative bending moment produced along the wall stem responsible for resisting the deflection of the wall away from the backfill was found to be increased with the increase in width factor of the shelf from 0.05 to 0.20, which in case of the simple wall without shelf was almost negligible.



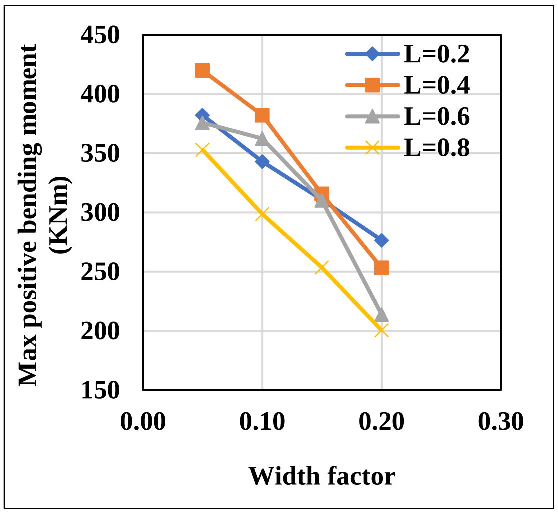
(a) (b)

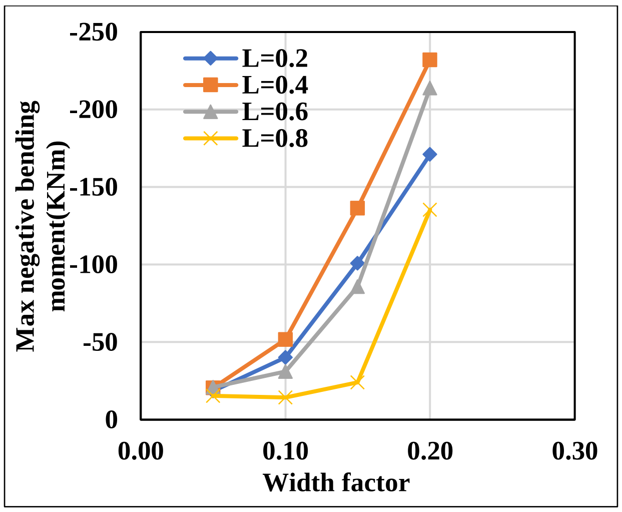




(c) (d)

Figure 4.7. Bending moment along the wall for location factor, (a). 0.2, (b). 0.4, (c). 0.6, and (d). 0.8, for single relief shelf





(a) (b)

Figure 4.8. Variation of (a). maximum positive and (b). maximum negative bending moment along the wall with width factor, for single relief shelf

4.3.2. Effect of location factor

To analyze the influence of location factor (L) on the stability of retaining wall 24 models were analyzed where location factor was varied from 0.2 to 0.8 for different cases of width factor (0.05, 0.10, 0.15, and 0.20).

4.3.2.1. Active earth pressure (P_a)

When the location of the relief shelf was lowered down by varying the location factor from 0.2 to 0.8, it was observed that maximum earth pressure and lateral thrust on the wall reduced while going from location factor 0.2 to 0.4. But when the shelf was further lowered down below location factor 0.4, both maximum earth pressure and lateral thrust started to increase; but the lateral thrusts in all the cases were less than that of retaining wall without shelves (Figures 4.9 and 4.10).

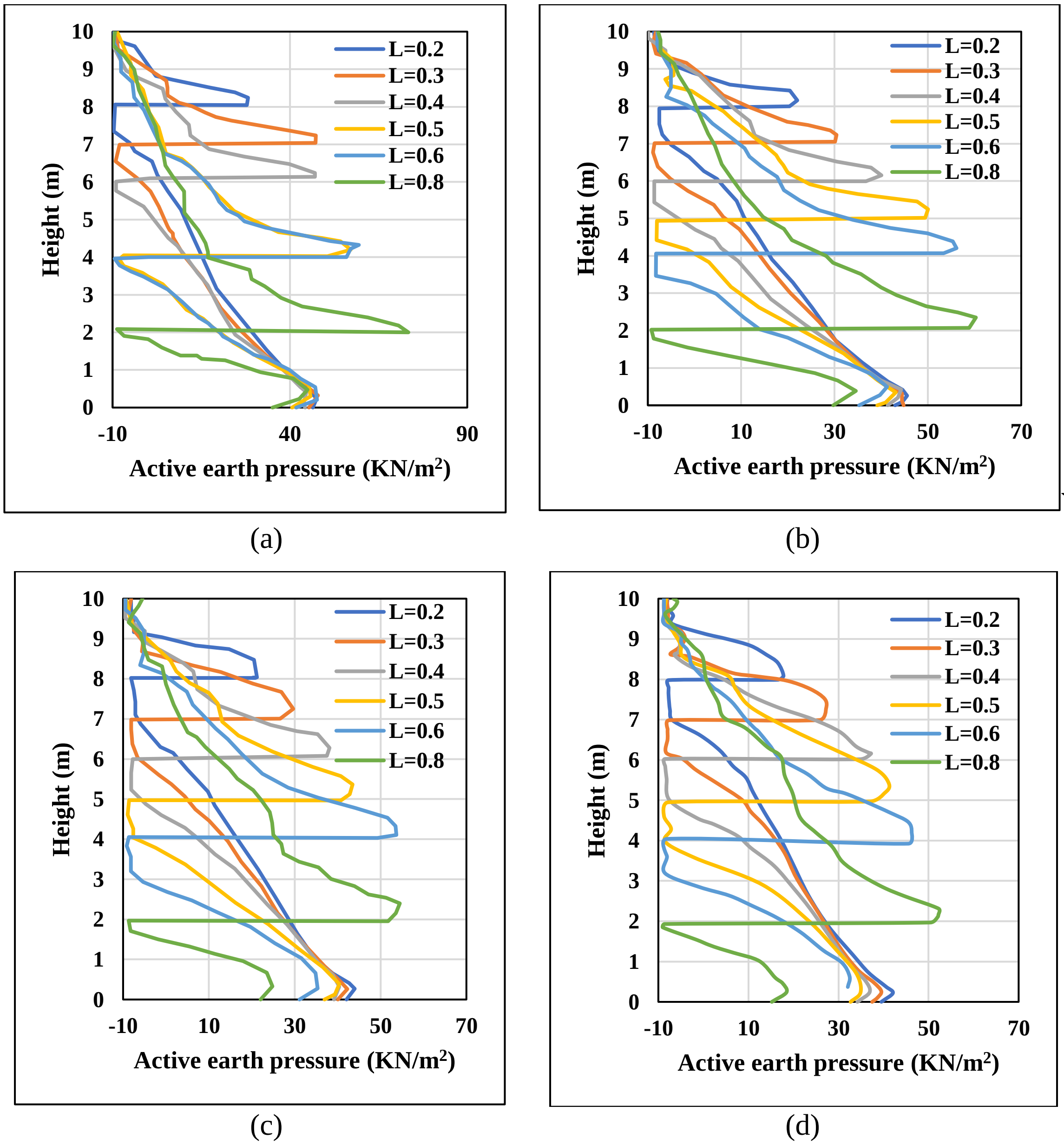
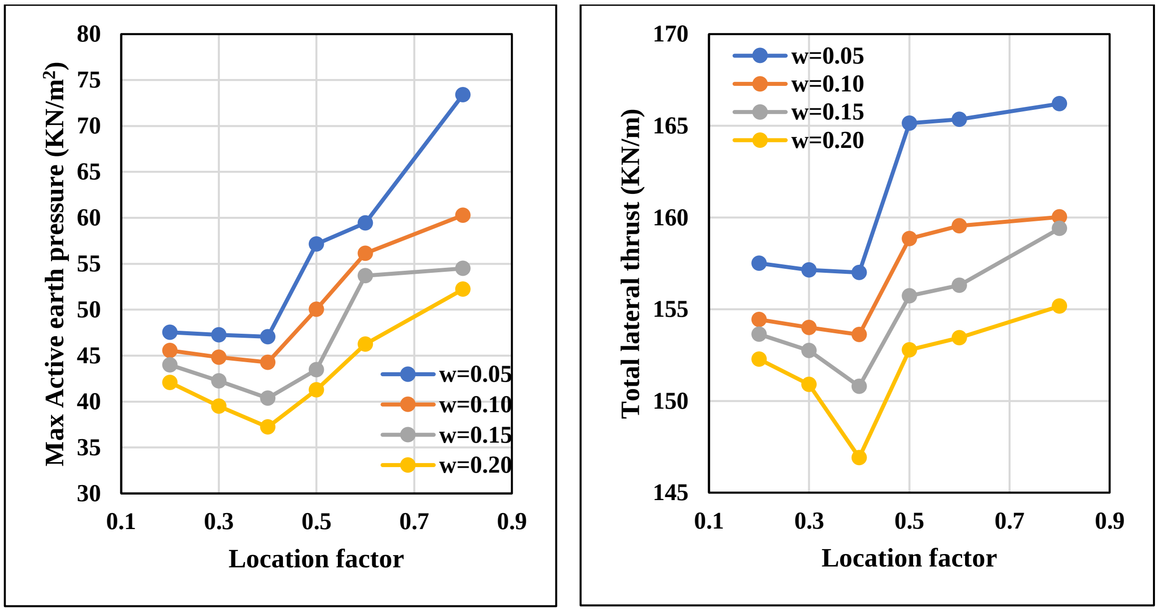


Figure 4.9. Active earth pressure distribution for width factor (a). 0.05, (b). 0.10, (c). 0.15, and (d). 0.20, for single relief shelf



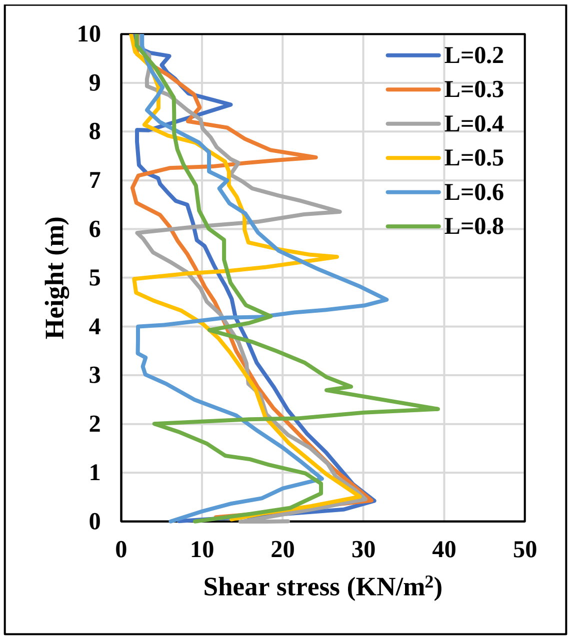
(a) (b)

Figure 4.10. Variation of (a). maximum earth pressure and (b). lateral thrust on the wall with location factor, for single relief shelf

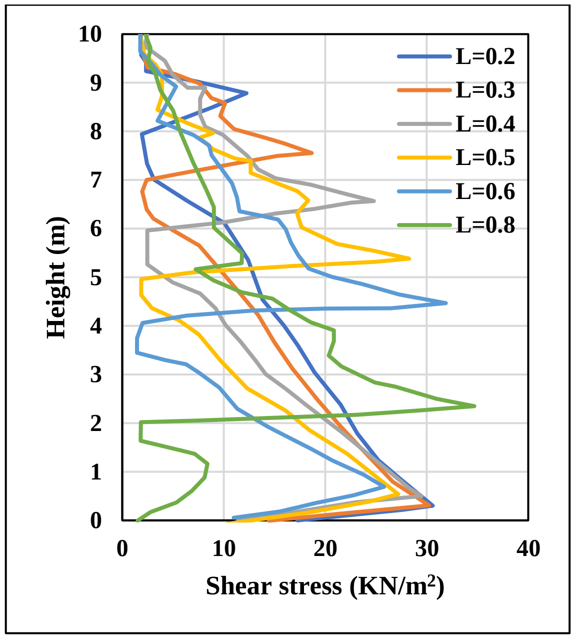
Maximum active pressure was observed to be reduced up to 3.7, 9.40, 17.38, and 23.83 percent for width factors 0.05, 0.10, 0.15, and 0.20, respectively, for the location factor of 0.4. But by increasing the location factor further from 0.4 to 0.8, it started to increase up to 50.21 percent from simple cantilever, when the width factor was 0.05. Similarly, lateral thrust on the wall in all the cases was found to be reduced, with optimum reduction when location factor 0.4 was used. Reductions in the lateral thrust of 5.62 percent for location factor 0.8 and width factor 0.05 and 16.58 percent for location factor 0.4 with width factor 0.20 were observed. On the other hand, Shehata (2016) found a location factor of 0.3 to be the optimum one to reduce the lateral thrust on the wall.

4.3.2.2. Shear stress (S)

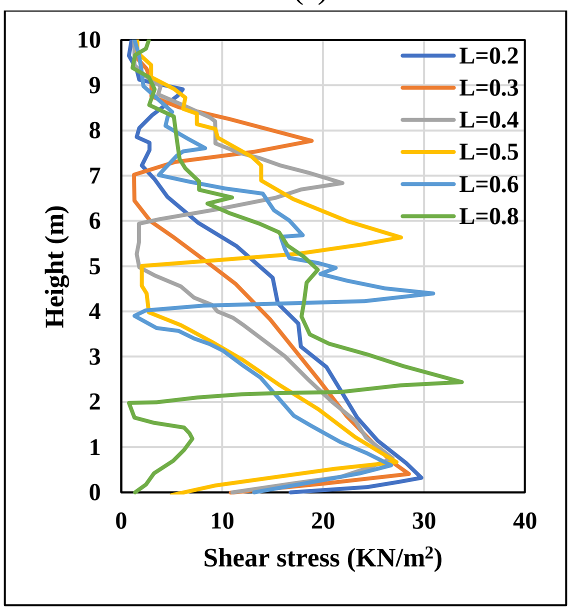
The shear stress diagram was influenced significantly with the introduction of shelves at different locations (Figure 4.11). It was observed that for width factors 0.05 and 0.10, the minimum value of shear stress was obtained when location factor of 0.5 was used, while, for width factors 0.15 and 0.20, when location factor was varied between 0.2 and 0.8, the location factor which reduced the shear stress the most was 0.4 (Figure 4.12). Maximum reduction in shear stress at with shelf at location factor 0.4 was found to be 21.79 percent.



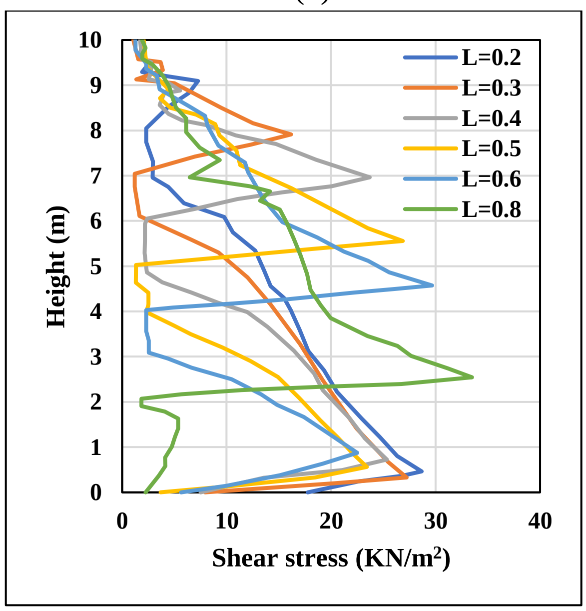
(a)



(b)



(c)



(d)

Figure 4.11. Shear stress along the wall for width factor (a). 0.05, (b). 0.10, (c). 0.15, and (d). 0.20, for single relief shelf

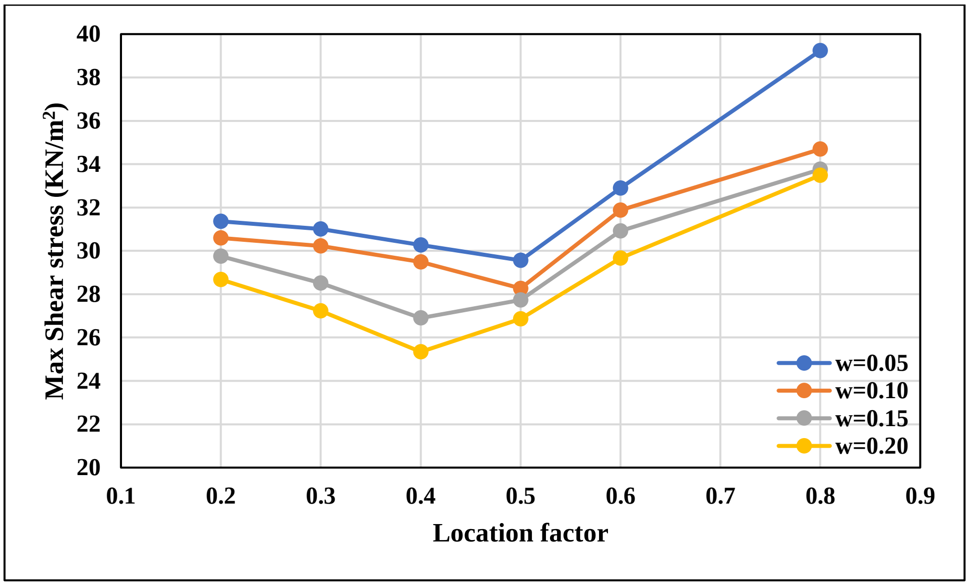
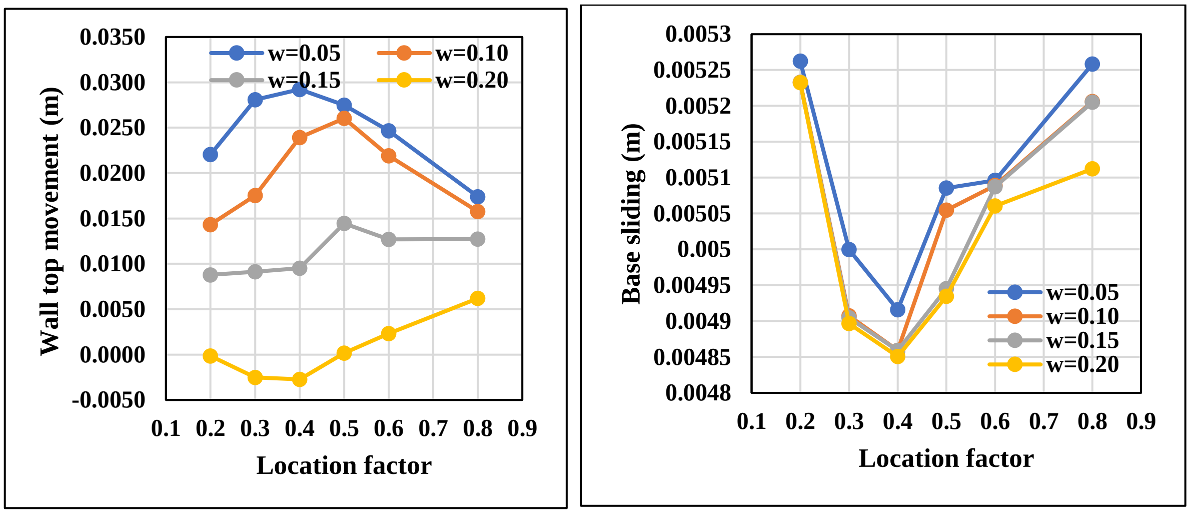


Figure 4.12. Variation of maximum shear stress along the wall with location factor, for single relief shelf

4.3.2.3. Wall top movement (D_T) and base sliding (D_S)

After the analysis, it was observed that for width factors 0.05, 0.10, and 0.15, as the location factor was increased from 0.2 to 0.4 or 0.5, wall top movement tends to increase. But then started to decrease as the location factor was further increased to 0.8. In contrast, for width factor 0.20 retaining wall experienced minimum wall top movement at location factor 0.4 and increased when the shelf was lowered down (Figure 4.13(a)). Reduction in the range of 3.83 to 114.98 percent was obtained, with maximum reduction for the case when the relief shelf of width factor 0.2 was attached at the location factor of 0.4. Whereas, Shehata (2016) observed optimum reduction in wall top movement for the case when the shelf's location factor was 0.3.

Regarding base sliding, identical behavior was shown by the retaining wall for all the cases of width factor. It was observed that minimum base sliding was encountered when the location factor was set as 0.4 (Figure 4.13(b)). Reduction in the range 22.53 to 28.57percent was obtained in base sliding among different cases.

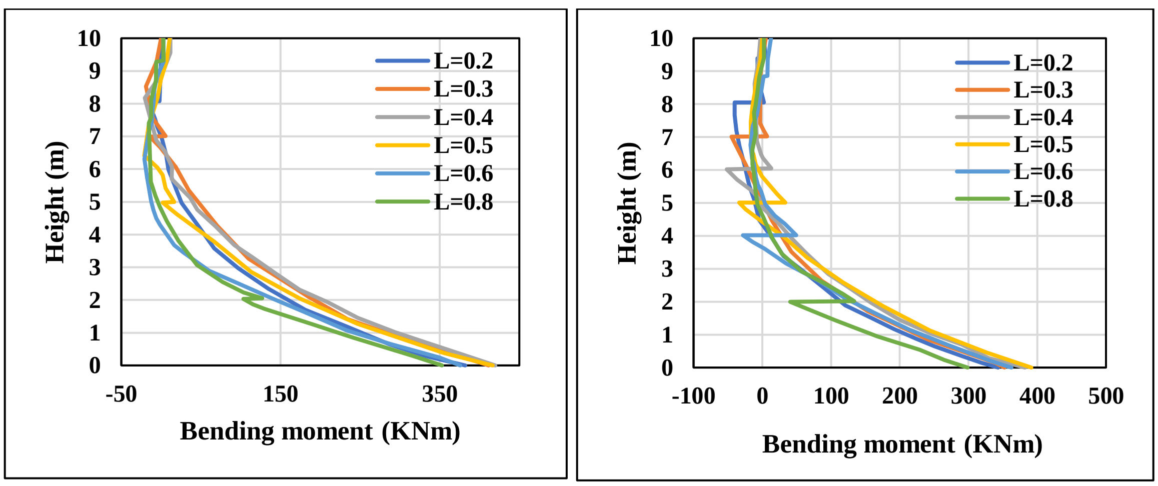


(a) (b)

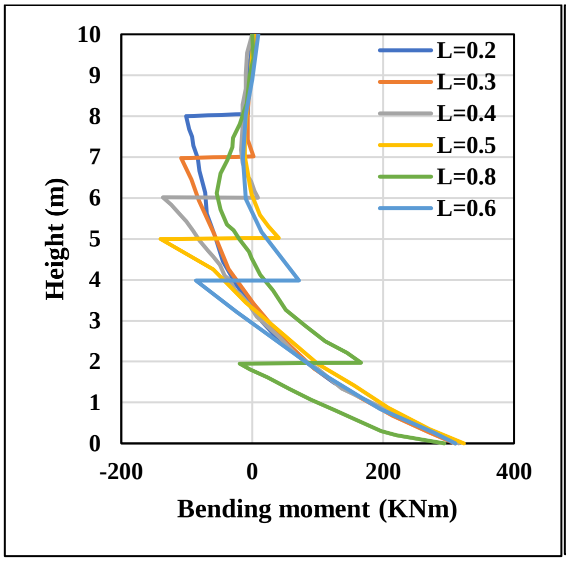
Figure 4.13. Variation of (a). wall top movement and (b). base sliding, with location factor, for single relief shelf

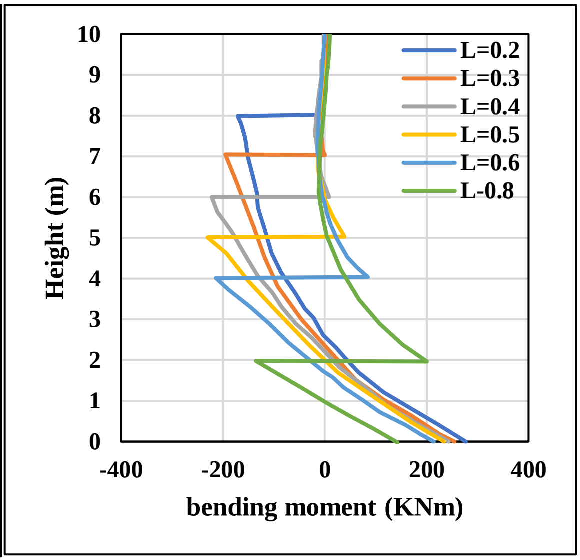
4.3.2.4. Bending moment (M)

Significant changes were observed in the bending moment diagram of the retaining wall as can be seen in Figure 4.14. For width factor 0.05 the maximum bending moment along the wall increased as the location factor was increased from 0.2 to 0.5 and then started to decrease onwards. This behavior began to fade away as the width factor was increased to 0.2 and the variation became more and more linear as can be seen in Figure 4.15 (a). The latter case's results tie well with that of Shehata (2016), while for shelves with width factors less than 0.2, the trend of maximum overturning moments is in contrast as compared to the findings of Shehata (2016).



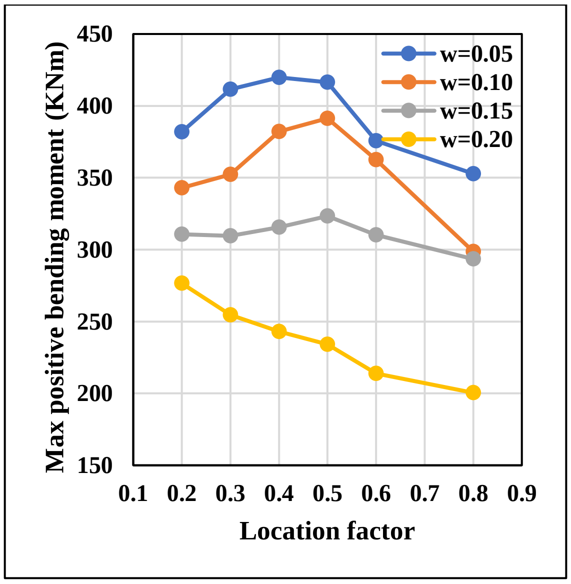
(a) (b)

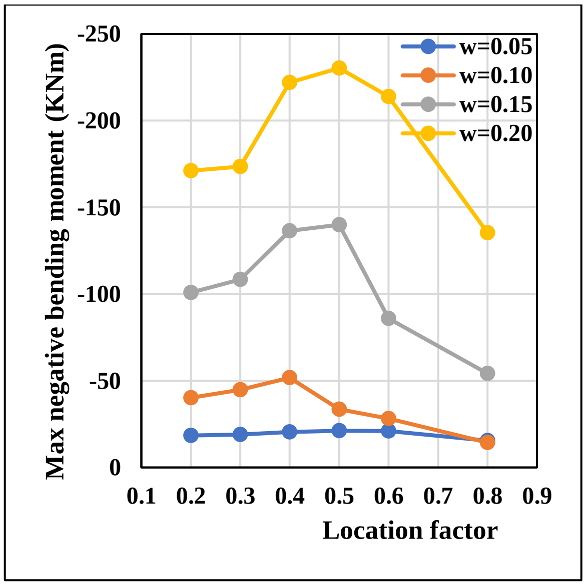




(c) (d)

Figure 4.14. Bending moment along the wall for width factor (a). 0.05, (b). 0.10, (c). 0.15, and (d). 0.20, for single relief shelf





(a) (b)

Figure 4.15. Variation of (a). maximum positive and (b). maximum negative bending moment along the wall with location factor, for single relief shelf

Maximum reduction in the positive bending moment up to 47.28 percent was obtained for the location factor 0.8 and width factor 0.20. Similarly, the same behavior was observed for a negative bending moment along the wall which resists the bending of the wall away from the backfill (Figure 4.15(b)).

4.3.3. Effect of thickness

To study the impact of thickness on the wall's stability, a combination of width factor and location factor had to be chosen, which for the present study are 0.15 and 0.4, respectively, and thickness to be varied from 0.2 m to 0.4 m.

4.3.3.1. Active earth pressure (P_a)

The active earth pressure distributions on the wall for different thicknesses of relief shelves were very adjacent to each other (Figure 4.16). Though the difference was very small but maximum earth pressure, as well as lateral thrust on the wall, were decreased as the thickness of the shelf was increased (Figure 4.17). Similar results were found by Shehata (2016) for different thicknesses of the relief shelf. But one should be careful when using the thinner relief shelf as it will deflect more and can break away. Hence, the use of the shelf introduces a new failure mechanism in the retaining structure; therefore, it is not recommended to use very flexible shelves.

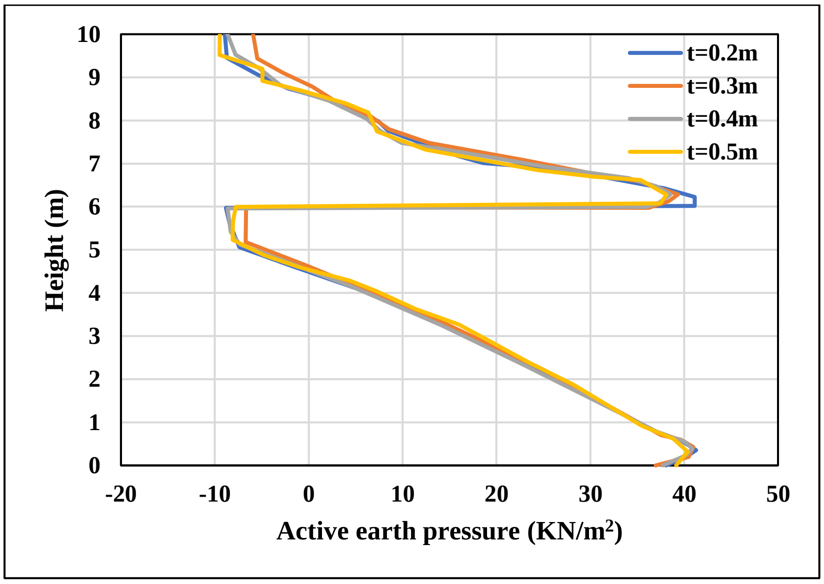
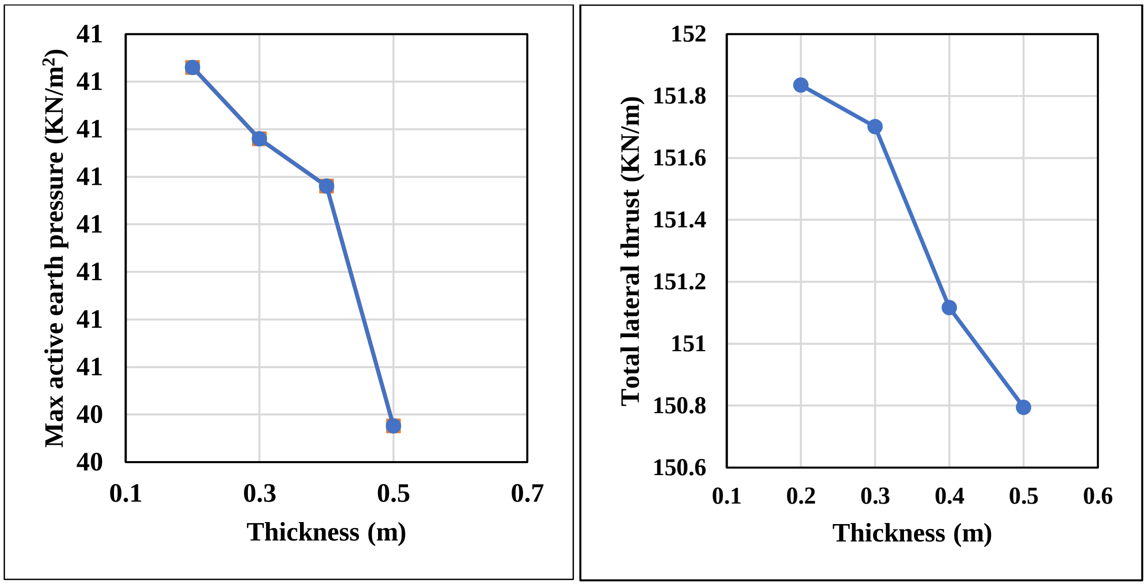


Figure 4.16. Active earth pressure distribution for different thicknesses of relief shelf, for single relief shelf



(a) (b)

Figure 4.17. Variation of (a). maximum earth pressure and (b). lateral thrust on the wall with a thickness of relief shelf, for single relief shelf

4.3.3.2. Shear stress (S)

Not much difference was observed in shear stresses were observed by changing the thickness of the wall (Figure 4.18), but nevertheless, it was decreased as the shelf thickness was increased by a small number (Figure 4.19).

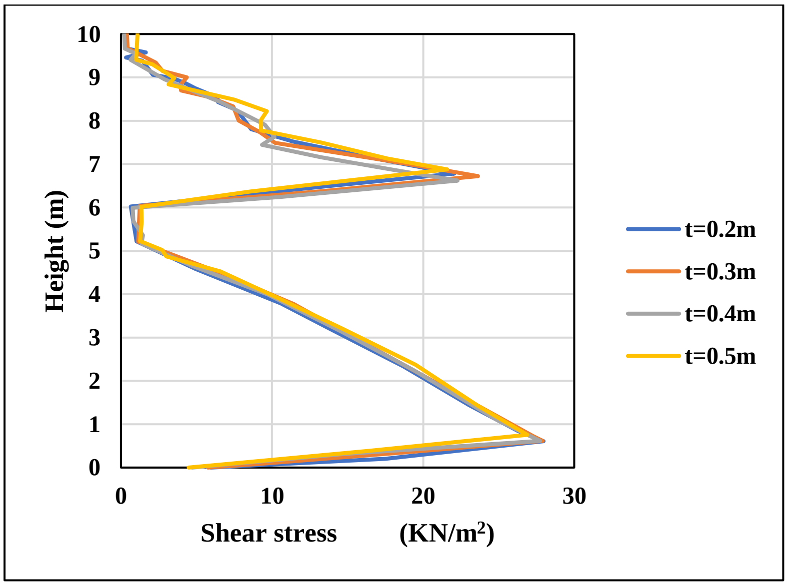


Figure 4.18. Shear stress on the wall for different thicknesses of the relief shelf, for single relief shelf

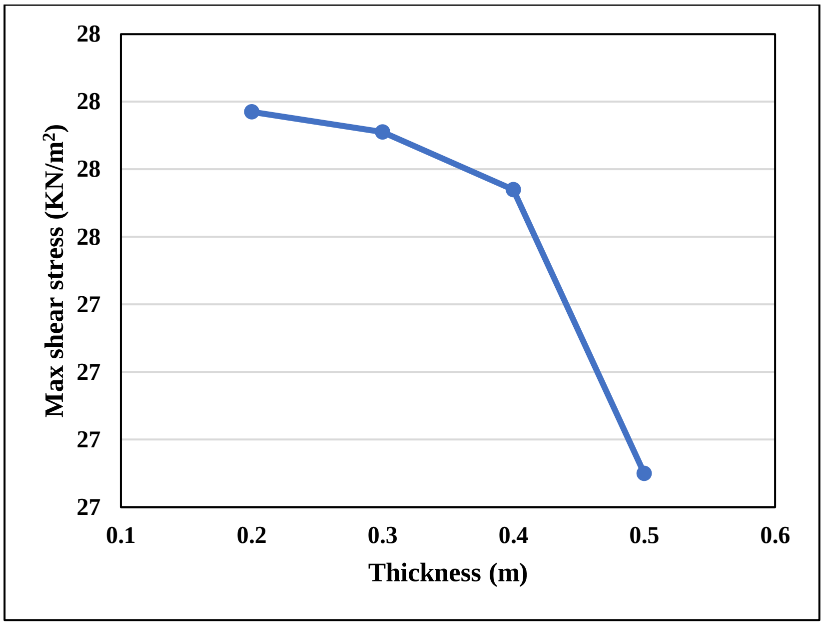
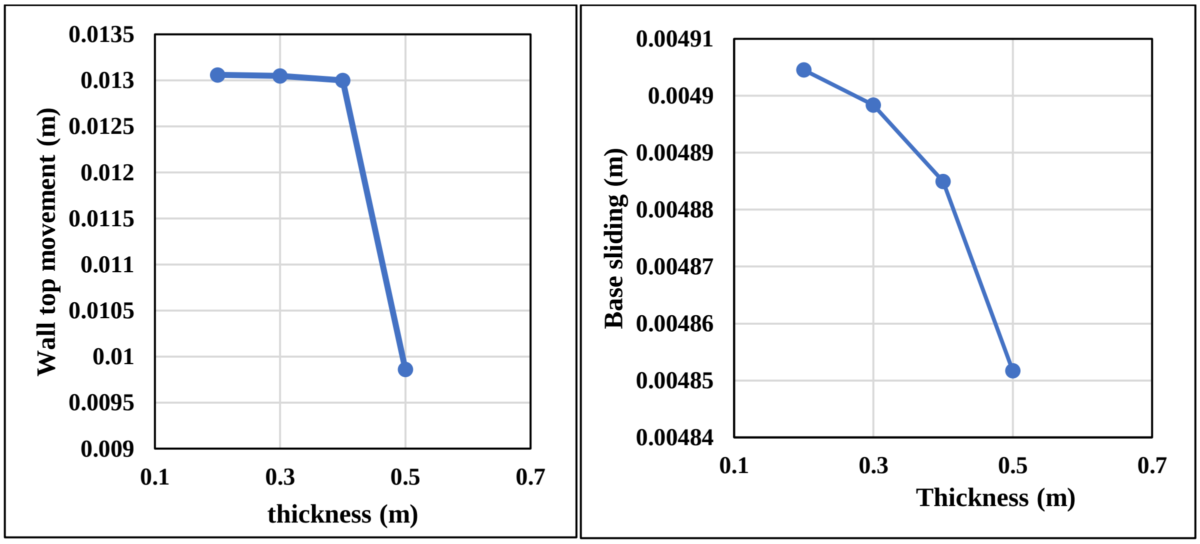


Figure 4.19. Variation of maximum shear stress with the thickness of relief shelf, for single relief shelf

4.3.3.3. Wall top movement (D_T) and base sliding (D_S)

Both wall top movement and base sliding of the retaining wall was reduced by a small value when the thickness of the shelf was increased from 0.2 m to 0.5 m (Figure 4.20).



(a) (b)

Figure 4.20. Variation of (b). wall top movement and (b). base sliding with the thickness of relief shelf, for single relief shelf

4.3.3.4. Bending moment (M)

Bending moment diagrams for different thicknesses of the shelf were also very similar to each other (Figure 4.21). With a very small difference, the positive bending moment along the wall as reduced from 320.39 kNm to 315.23 kNm with an increase in the thickness of the shelf from 0.2m to 0.5m, respectively (Figure 4.22).

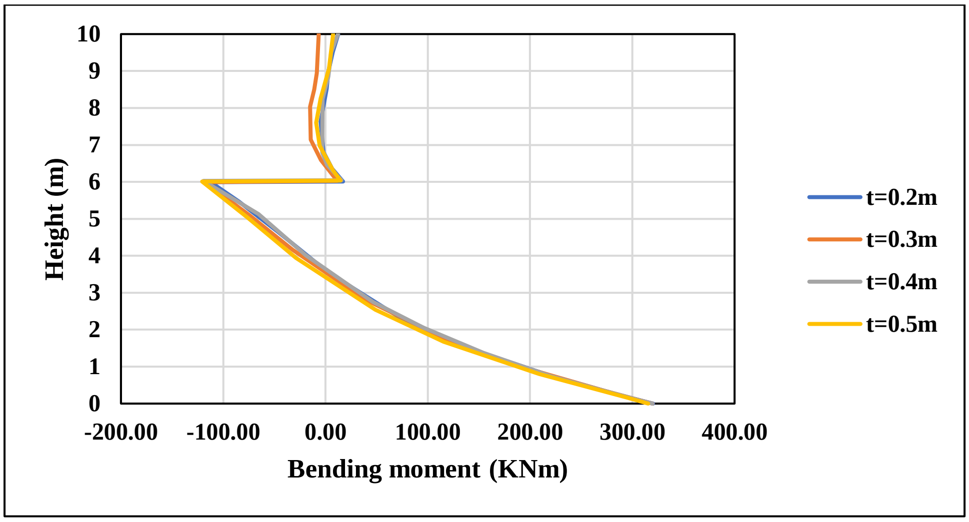
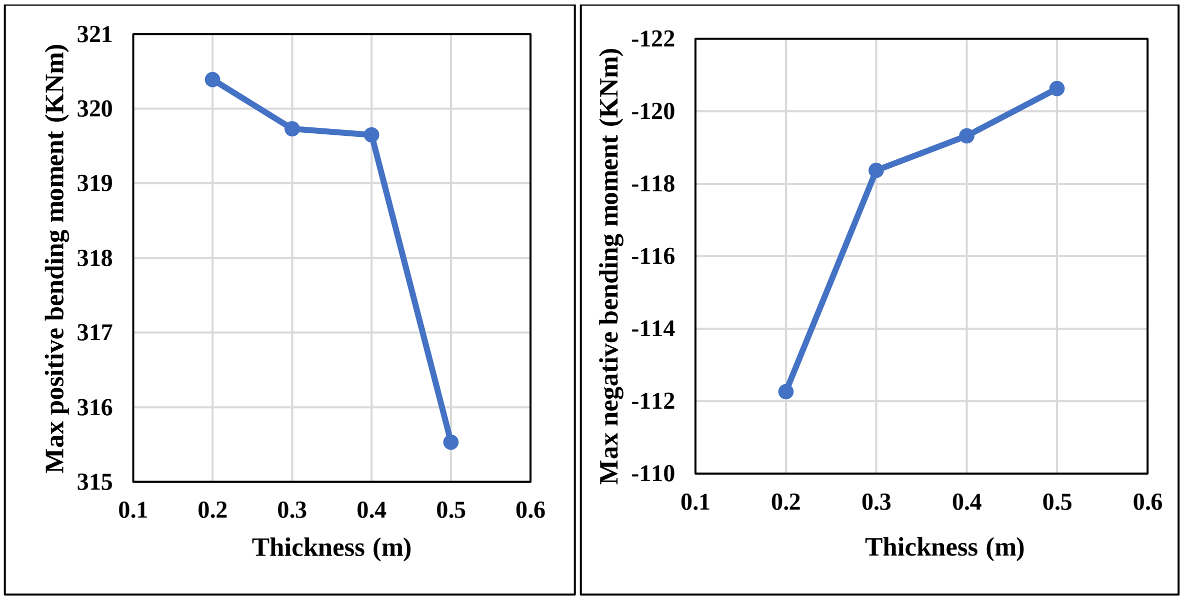


Figure 4.21. Bending moment along the wall for different thicknesses of relief shelf, for single relief shelf



(a) (b)

Figure 4.22. Variation of (a). maximum positive and (b). maximum negative bending moment along the wall with the thickness of relief shelf, for single relief shelf

4.3.4. Best combination of parameters in case of single relief shelf

After analyzing the influence of each of the parameter of the relief shelf on the stability of retaining wall, the best combination of parameters was found to be the one when location factor, width factor, and thickness of 0.4, 0.20, and 0.5 m, respectively were used, as it produced better results among all the models analyzed within the scope of the present study. In the described case, maximum active earth pressure and total lateral thrust on the wall of 37.22 kN/m^2 and 146.91 kN/m were produced respectively, which produced the overturning moment of 253.15 kNm (36.05 percent less than that of the simple wall without shelf) and maximum shear stress of 25.34 kN/m^2. Moreover, wall top movement was reduced from 0.01824 m in case of the simple wall to -0.00273 m, along with a significant reduction in base sliding from 0.00679 m to 0.00485 m. For this combination, the factor of safety against sliding and overturning were also estimated which were found to be improved significantly from 1.52 to 1.92 and 1.15 to 2.58, respectively. The improvement in the stability results is illustrated in Table 4.1 below.

Table 4.1. Effect of optimum parameters of single relief shelf on the stability of retaining wall

S. No	Result	Reduction	Increase
1	Maximum active earth pressure (kN/m^2)	23.84 %	-
2	Lateral thrust (kN/m)	16.58 %	-
3	Shear stress (kN/m^2)	21.79 %	-
4	Wall top movement (m)	114.9 %	-
5	Base sliding (m)	28.57 %	-
6	Overturning bending moment (kNm)	36.05 %	-
7	Factor of safety against overturning	-	55.42 %
8	Factor of safety against sliding	-	26.31 %

4.4. Retaining wall with two relief shelves

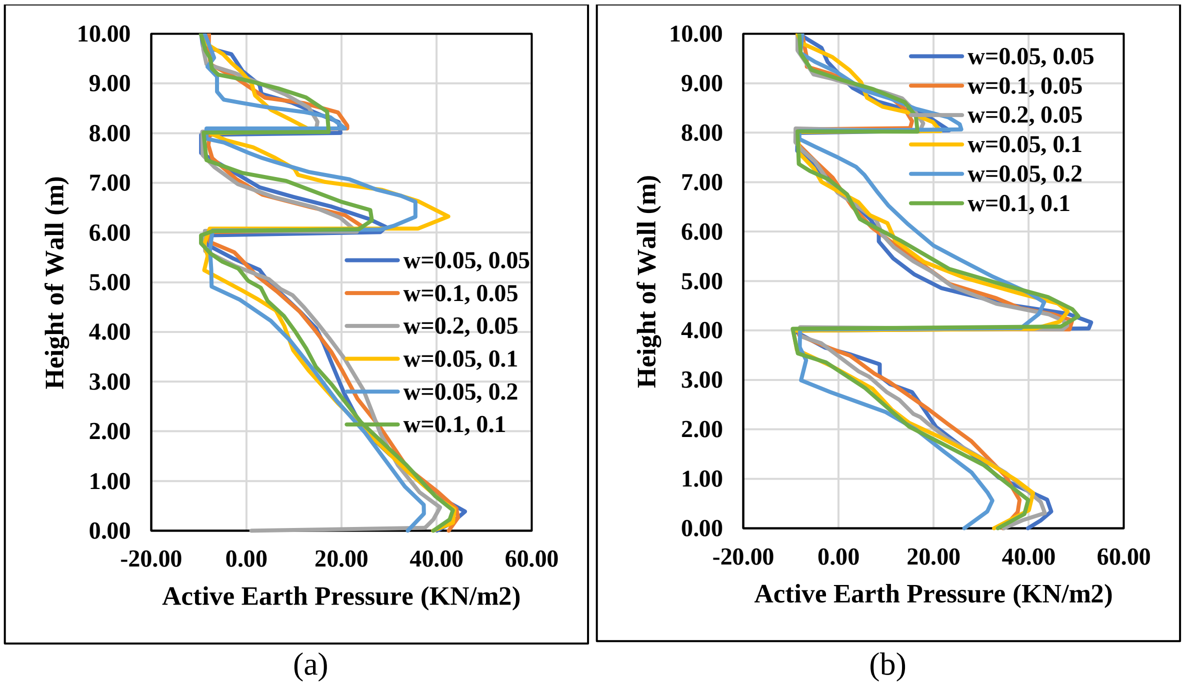
In this phase, 30 different models are developed and analyzed to examine the stability of retaining wall, supported with two relief shelves for active earth pressure, shear stresses, bending moment, wall top movement, and base sliding**.** Furthermore, the stability of the retaining walls is also evaluated for several combinations of width factors, location factors, and thicknesses as in Table 3.7 (section 3.6.2).

4.4.1. Effect of shelf width factor

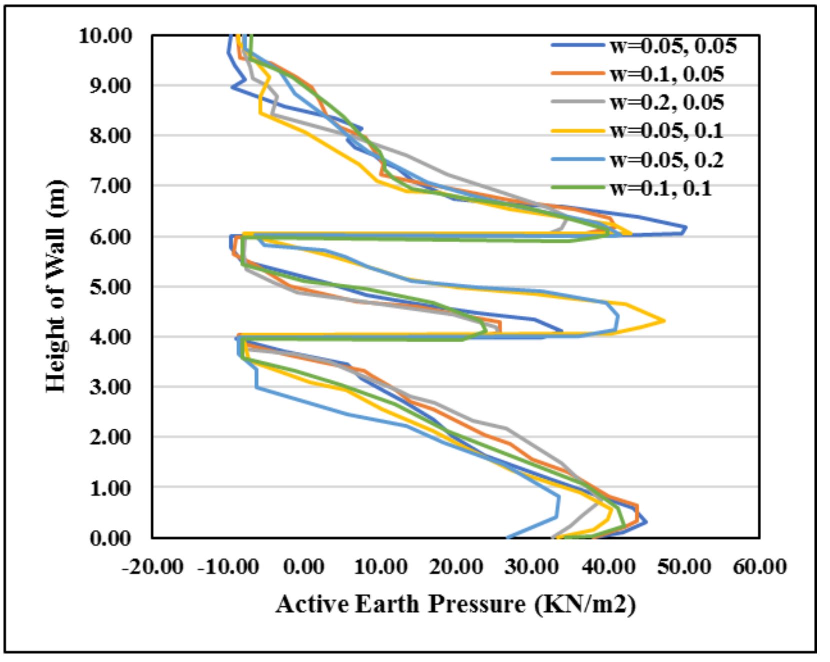
To analyze the effect of shelf width, 18 models are analyzed by keeping thicknesses constant at 0.5m and varying width factors of both the relief shelves from 0.05 to 0.20 for different location factors of 0.2 & 0.4, 0.2 & 0.6, and 0.4 & 0.6.

4.4.1.1. Active earth pressure (P_a)

Similar to the active earth pressure distribution for retaining wall with a single shelf, it was found to be terminated at both the locations of shelves and started from the far end beneath the shelves along with the formation of tension zones. In all the cases, as the width factor of one or both the shelves were increased the maximum value of active earth pressure on the wall as well as the lateral thrust on the wall was decreased, which can be seen in the Figures 4.23 and 4.24 below. The results were compatible with the ones found by Shehata (2016), where active earth pressure and total lateral thrust were reduced with the provision of two relief shelves, which was achieved when active pressure distribution was discontinued at the locations of shelves.

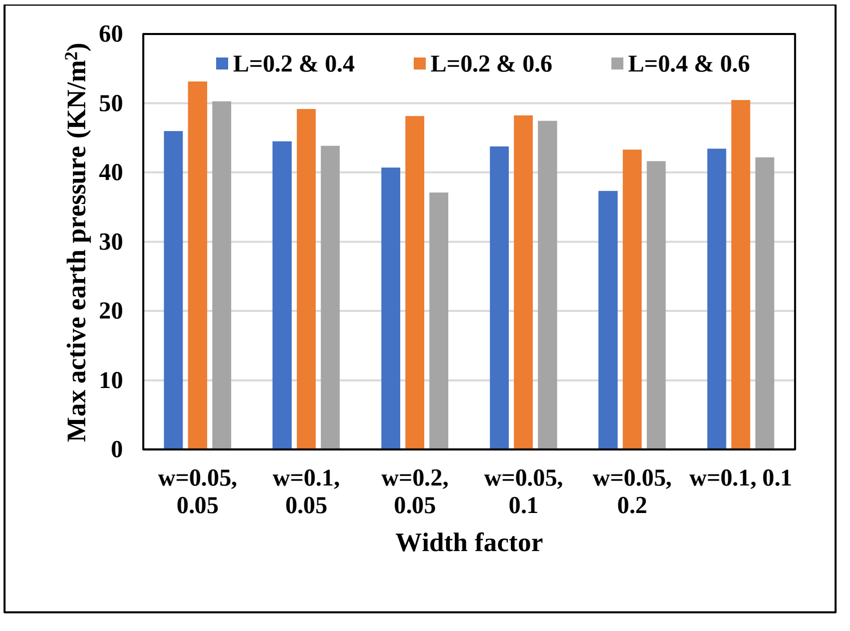


(a) (b)

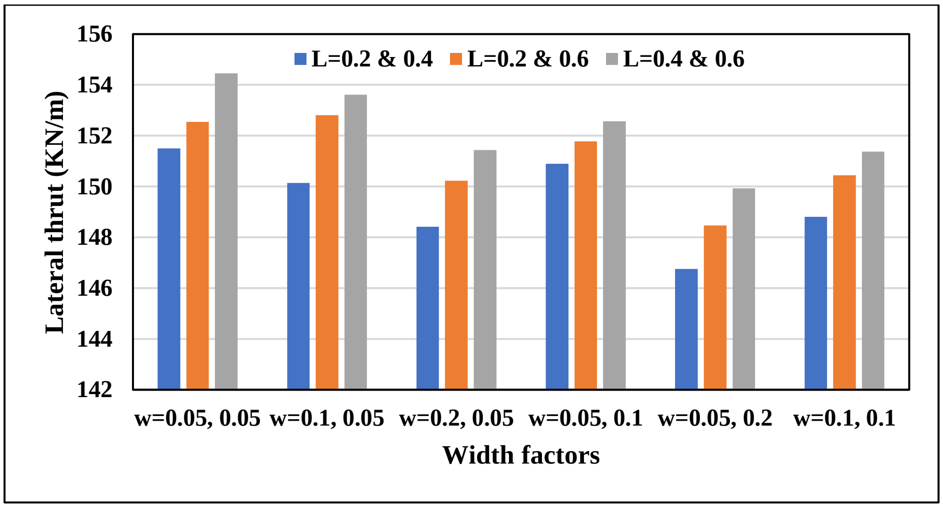


(c)

Figure 4.23. Active earth pressure distribution for location factors, (a). 0.2 & 0.4, (b). 0.2 & 0.6, for two relief shelves



(a)



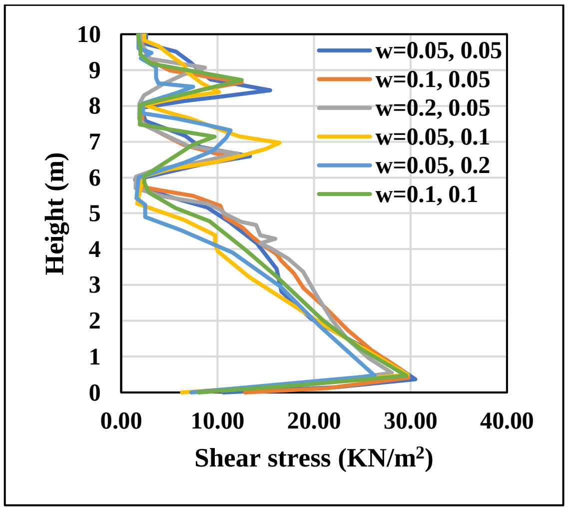
(b)

Figure 4.24. Variation of (a). maximum earth pressure and (b). lateral thrust on the wall with width factors of relief shelves, for two relief shelves

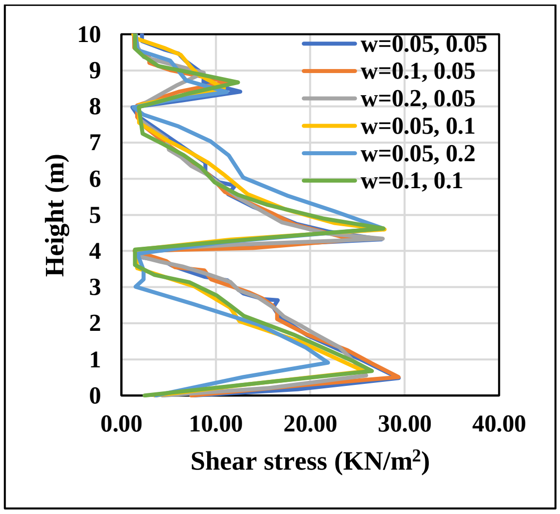
For all the three cases of different location factors, the maximum earth pressure along with the lateral thrust on the wall was reduced when shelf width of one or both the shelves was increased, with maximum reduction with the width factor of 0.2.

4.4.1.2. Shear stress (S)

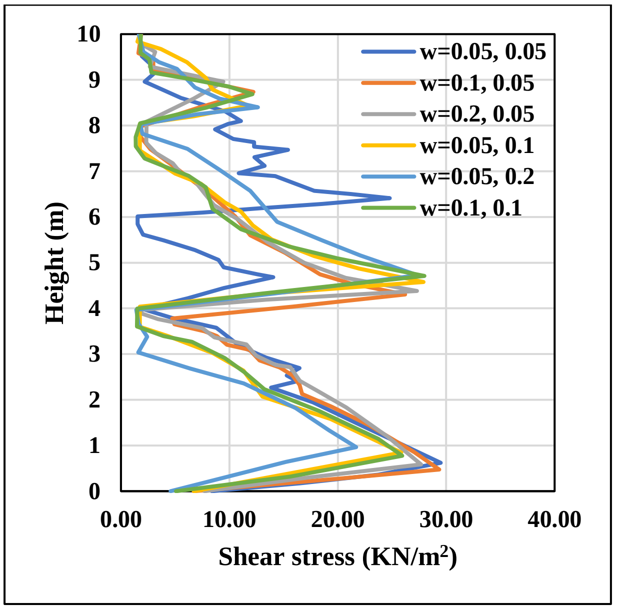
It was observed that for all the cases as the width factors of one or both the shelves were increased by keeping location factor constant in a particular case, the reduction occurred in the maximum value of shear stress along the wall, with maximum reduction achieved when width factors were increased to 0.2 (Figures 4.25 and 4.26).



(a)



(b)



(c)

Figure 4.25. Shear stress along the wall for location factors, (a). 0.2 & 0.4, (b). 0.2 & 0.6, for two relief shelves

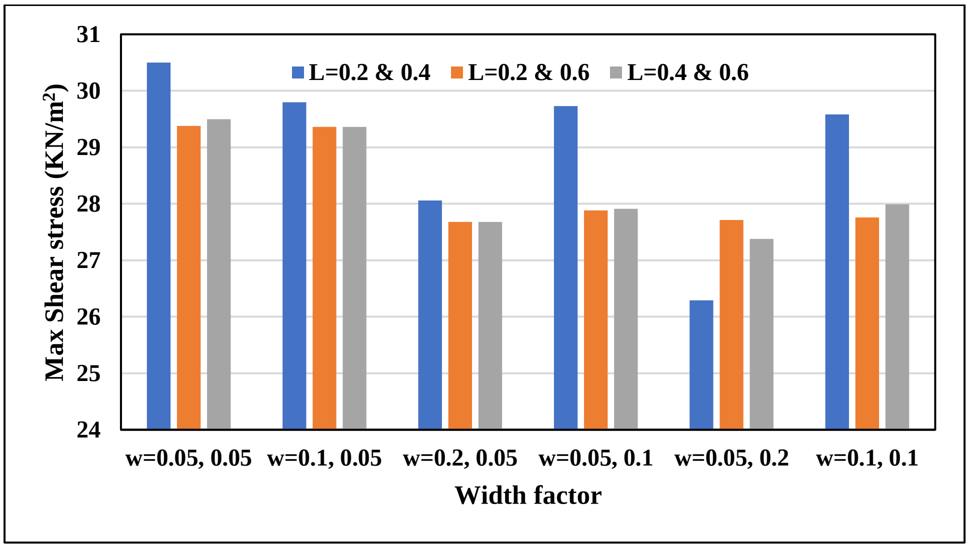


Figure 4.26. Variation of maximum shear stress with width factors for two relief shelves

4.4.1.3. Wall top movement (D_T) and base sliding (D_S)

Both wall top movement and base sliding of the wall was reduced when the width of one or both the shelves was increased in all the cases analyzed, with maximum reduction when shelf width was 0.2. In some cases, even the reduction in wall top movement was more than

100 percent as the wall didn't even deflect away from the backfill (Figures 4.27 and 4.28) in contrary to retaining wall without relief shelf.

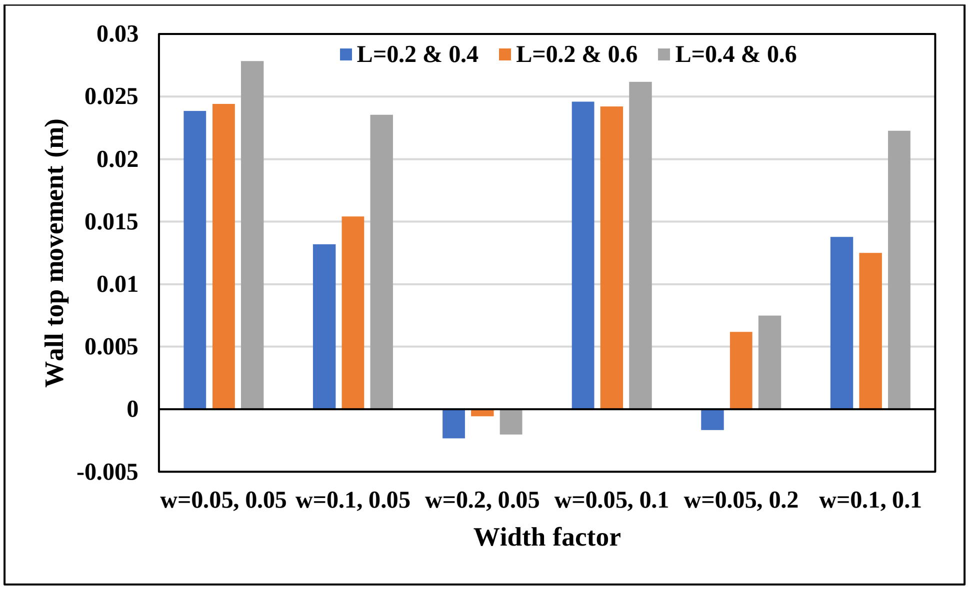


Figure 4.27. Variation of wall top movement with width factors for two relief shelves

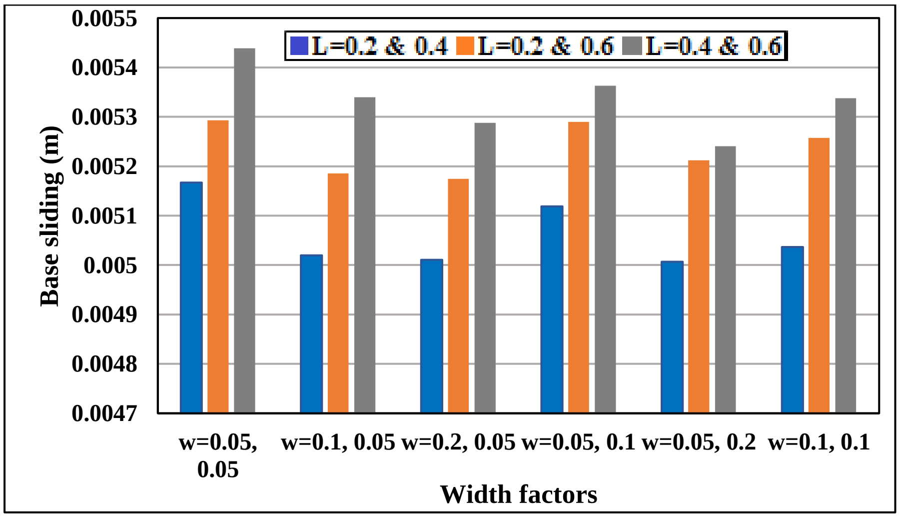


Figure 4.28. Variation of base sliding with width factors for two relief shelves

4.4.1.4. Bending moment (M)

Similar to retaining wall with single relief shelf, in the wall with 2 relief shelves when the width of one or both the shelves was increased the positive bending moment causing the wall to destabilize decreases (Figures 4.29 and 4.30), while negative bending moment increases which resist the bending of the wall away from the backfill (Figure 4.31). Maximum reduction of the bending moment was observed in the cases when one of the shelf's width factor was 0.2.

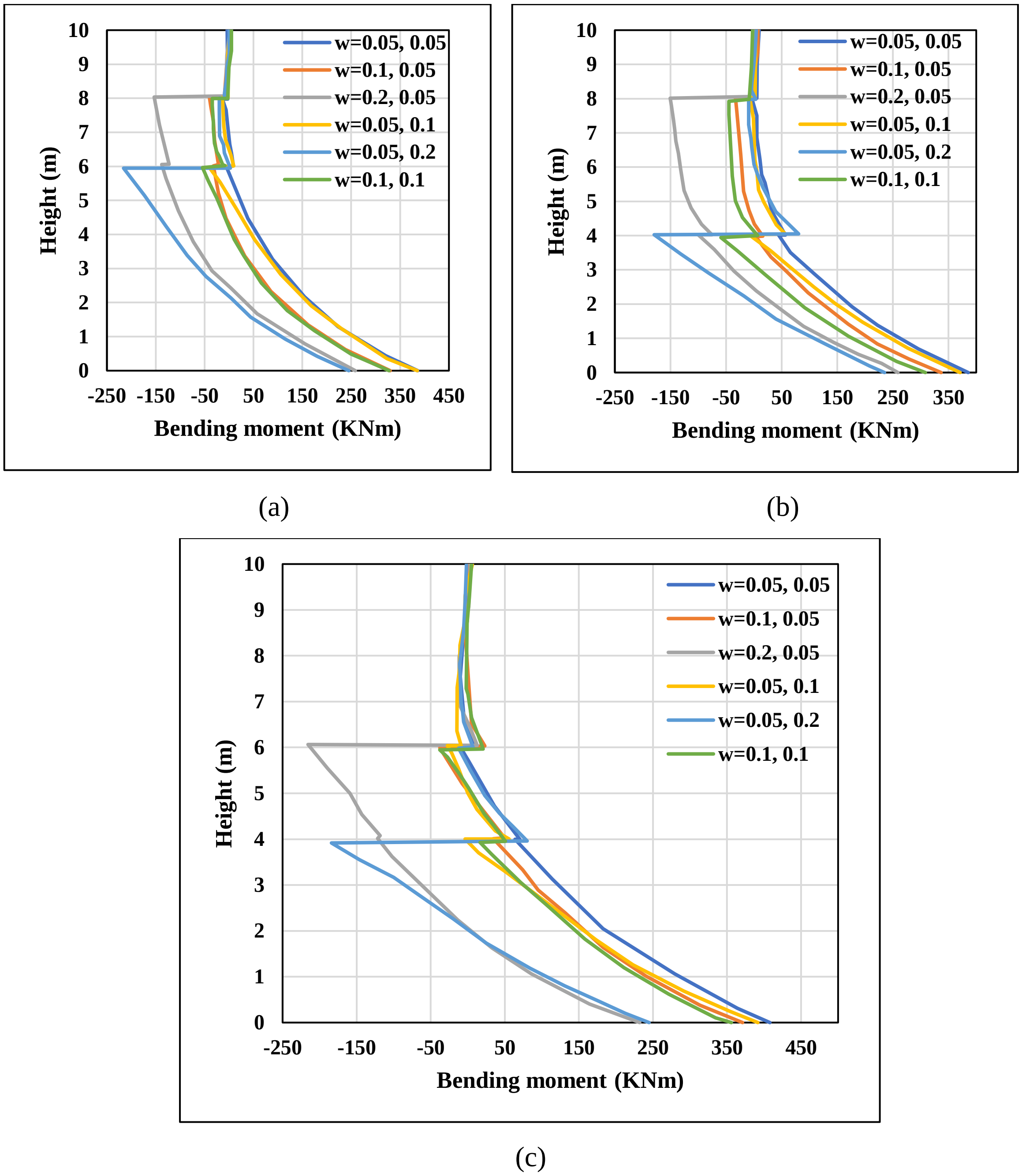


Figure 4.29. Bending moment along the wall for location factors, (a). 0.2 & 0.4, (b). 0.2 & 0.6, for two relief shelves

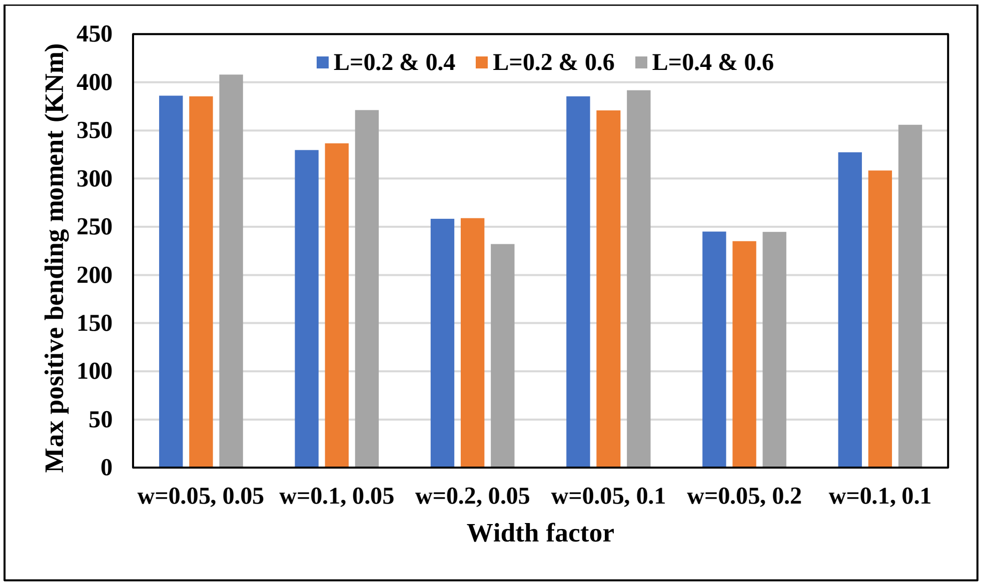


Figure 4.30. Variation of the positive bending moment with width factor, for different cases of location factors for two relief shelves

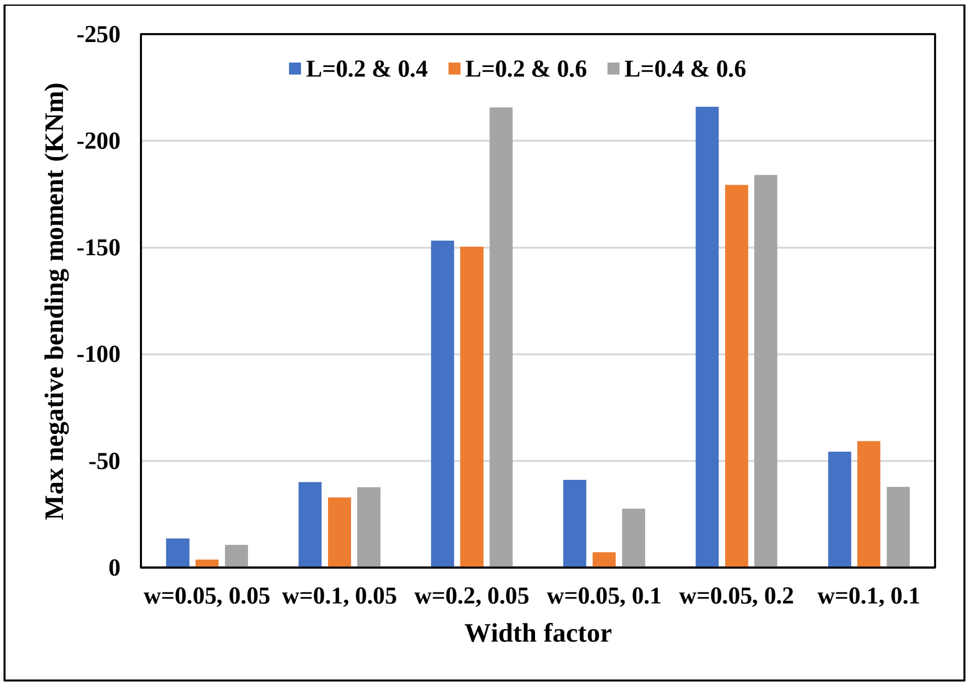


Figure 4.31. Variation of the negative bending moment with width factors for different cases of location factors for two relief shelves

4.4.2. Effect of location factor

To study the influence of location factor for two relief shelves, 9 models were made by keeping thickness and width factor to 0.5m and 0.15 for both the shelves, respectively, and changing the location factors as given in Table 3.7 (section 3.6.2).

4.4.2.1. Active earth pressure (P_a)

There were significant differences among the earth pressure distribution for different location factors as can be seen in Figure 4.32 below. Maximum reduction was obtained in case of minimum active pressure and lateral thrust on the wall when location factors 0.3 and 0.6 were used (Figures 4.33 and 4.32). Reduction in the range 0.9 percent (for location factors 0.2 and 0.8) to 28.52 percent (for location factor 0.3 and 0.6) was observed. Similarly, reduction in lateral thrust from 17.44 percent (for location factor 0.2 and 0.8) to 24.34 percent (for location factor 0.3 and 0.6) was noted.

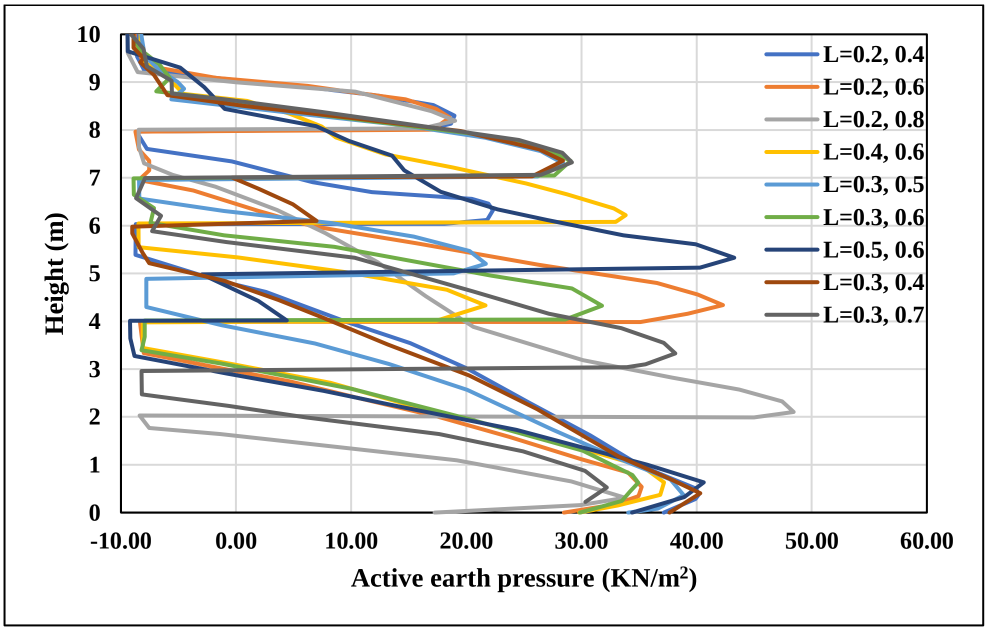


Figure 4.32. Active earth pressure distribution for different location factors for two relief shelves

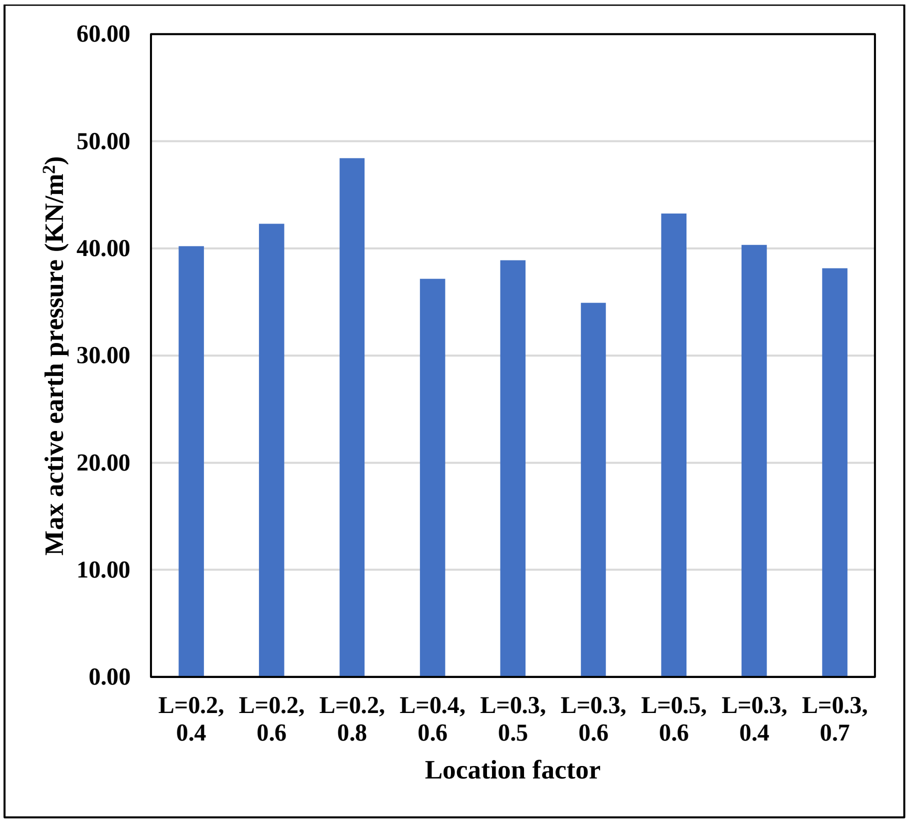


Figure 4.33. Variation of maximum active pressure with location factors for two relief shelves

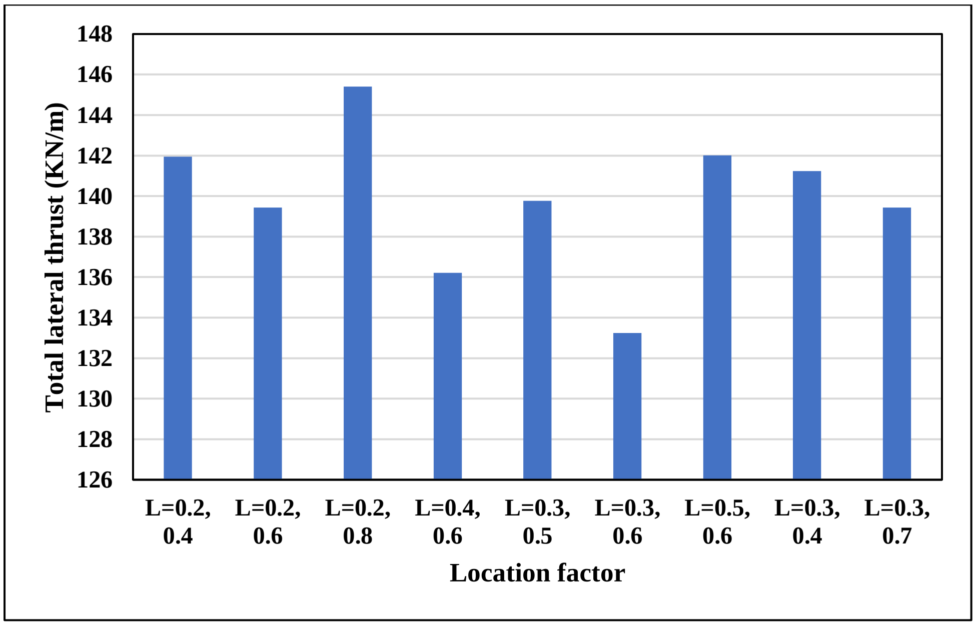


Figure 4.34. Variation of lateral thrust on the wall with location factors for two relief shelves

4.4.2.2. Shear stress (S)

In the case of shear stress on the wall, similar kinds of results were obtained as in case of active earth pressure. For some location factors values were on the higher side, while for others they were on the lower side (Figures 4.35). A maximum reduction in shear stress was obtained for the location factors 0.3 and 0.6 (Figure 4.36). Reduction from 4.07 percent (for location factor 0.2 and 0.8) to 22.25 percent (for location factor 0.3 and 0.6) was observed as compared to the wall without any shelf.

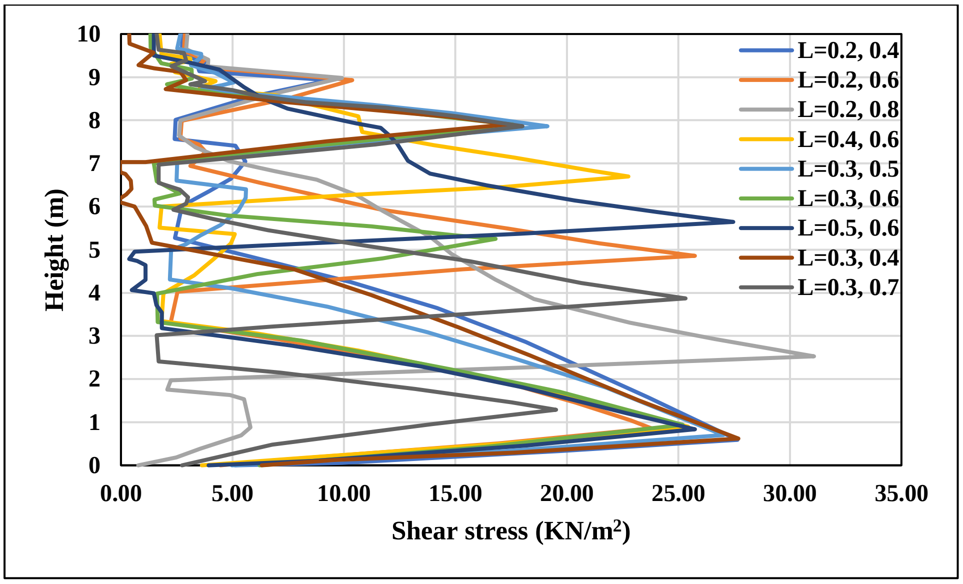


Figure 4.35. Shear stress along the wall for different location factors for two relief shelves

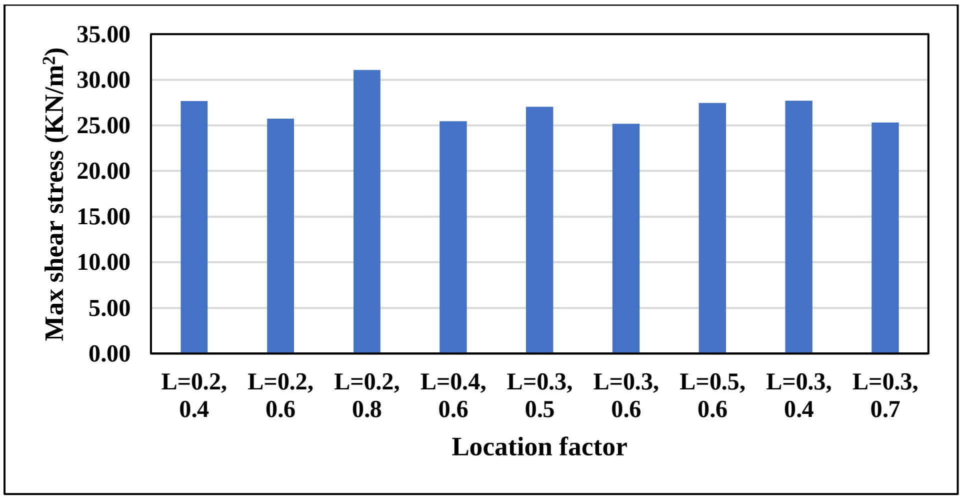


Figure 4.36. Variation of maximum shear stress along the wall with location factors for two relief shelves

4.4.2.3. Wall top movement (D_T) and base sliding (D_S)

Location factors had also a great influence on the wall top movement and base sliding. In all the cases observed wall top movement was less than that of simple cantilever wall with a reduction in the range from 66.72 percent (for location factor 0.5 and 0.6) to 85.14 percent (for location factor 0.3 and 0.6). Wall top movement of all the cases is shown in Figure 4.37.

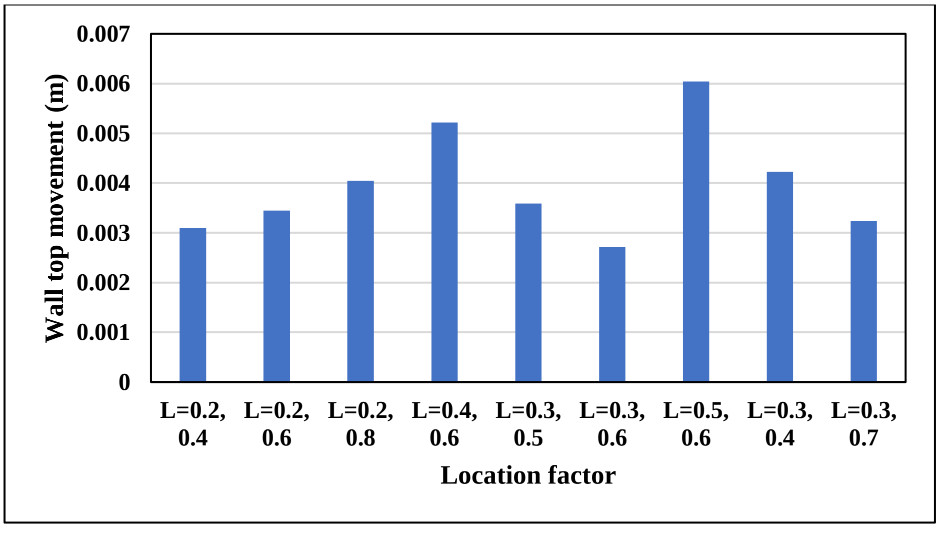


Figure 4.37. Variation of wall top movement with location factors for two relief shelves

Base sliding in all the cases observed was less than that of simple cantilever wall with reduction range from 18.85 percent (for location factor 0.2 and 0.8) to 31.66 percent (for location factor 0.3 and 0.6). the difference among the base sliding of all the cases was extremely small (Figure 4.38).

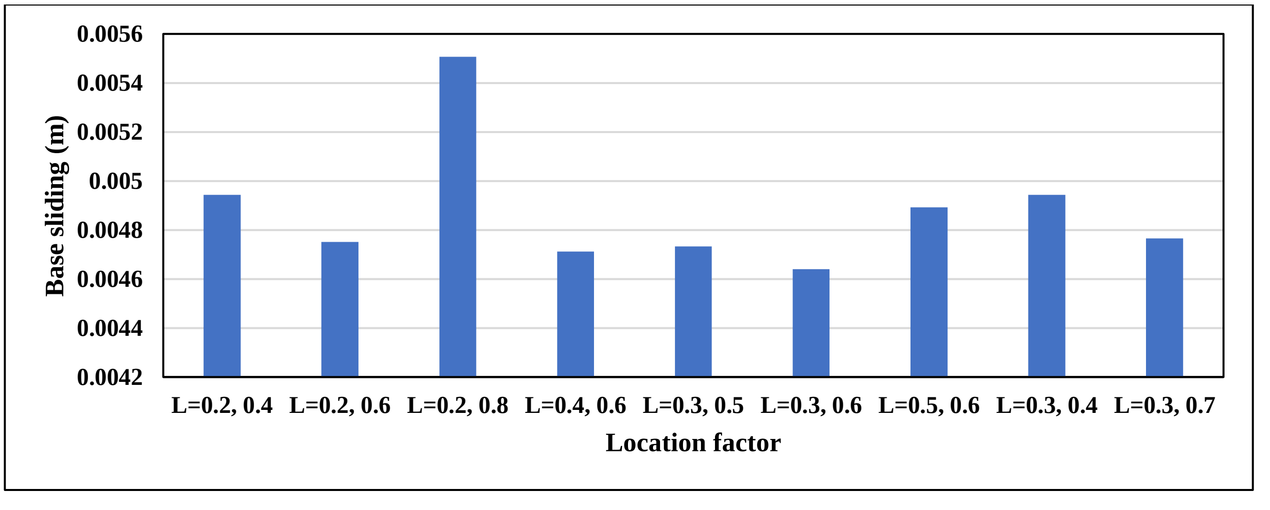


Figure 4.38. Variation of base sliding with location factors for two relief shelves

4.4.2.4. Bending moment (M)

Figure 4.39 illustrates the influence of using two relief shelves on the bending moment along the wall. The reduction of positive bending moment in the range from 22.44 percent (for location factor 0.5 and 0.6) to 41.96 percent (for location factor 0.2 and 0.8) was obtained. Positive bending moment values of all the cases can be seen in Figure 4.40 (a) below. Similarly, along with a decrease in the positive bending moment, a negative bending moment was increased in all the cases (Figure 4.40 (b)).

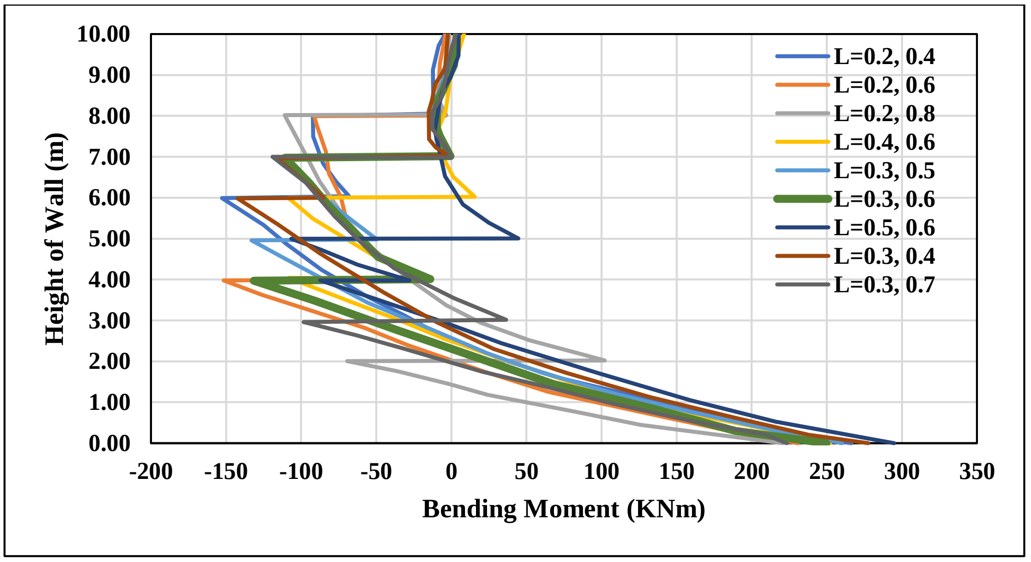
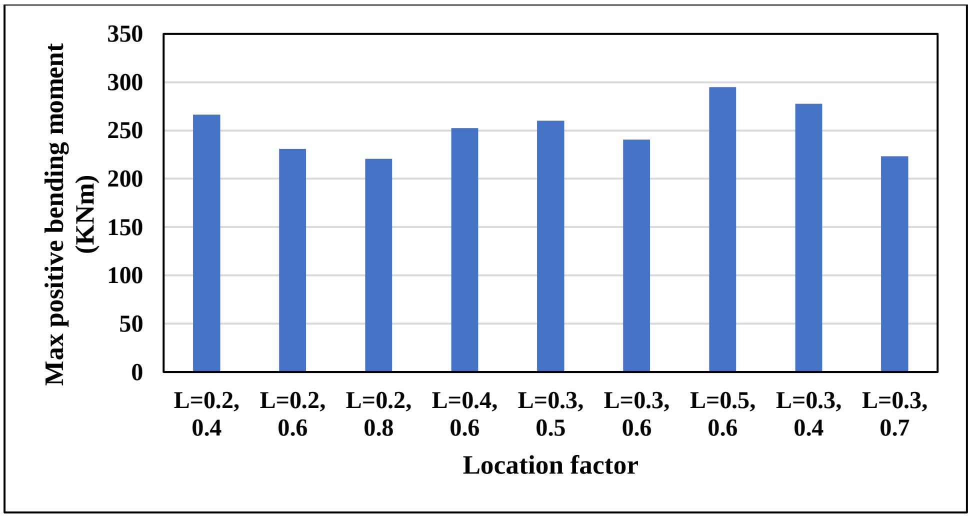
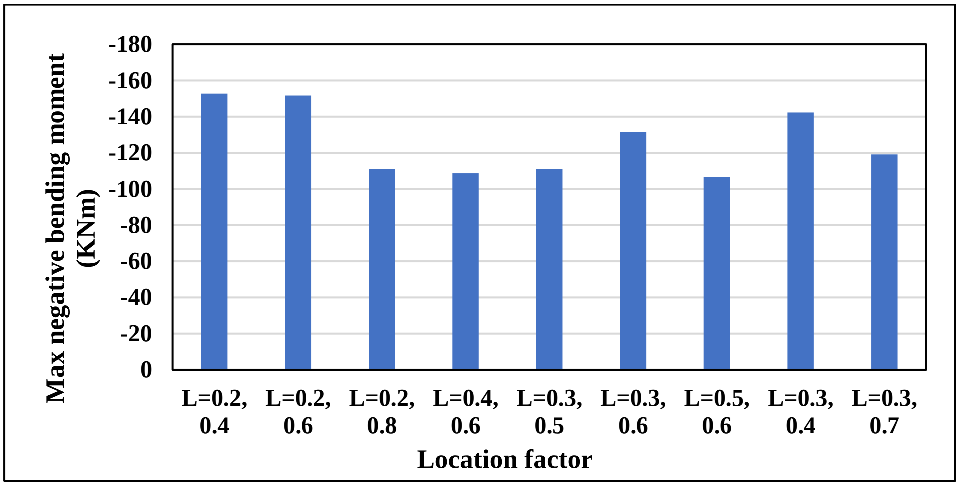


Figure 4.39. Bending moment along the wall for different location factors for two shelves



(a)



(b)

Figure 4.40. Variation of (a). maximum positive and (b). maximum negative bending moment with location factors for two relief shelves

4.4.3. Effect of thickness

4.4.3.1. Active earth pressure (P_a)

The active earth pressure distributions on the wall for different thicknesses of relief shelves were very adjacent to each other (Figure 4.41). Though the difference was very small but maximum earth pressure as well as lateral thrust on the wall were decreased as the thickness of the shelf was increased (Figure 4.42). But a discussed earlier, one should be careful when using the thinner relief shelf as it will deflect more and can break away.

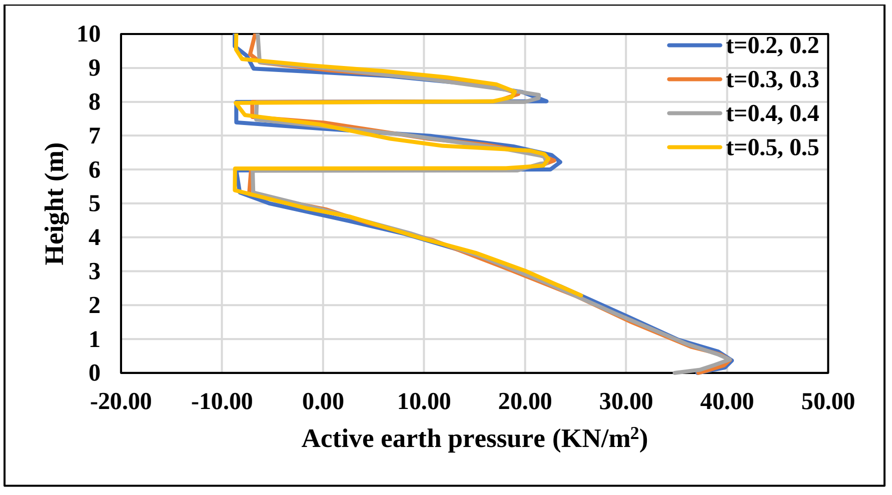
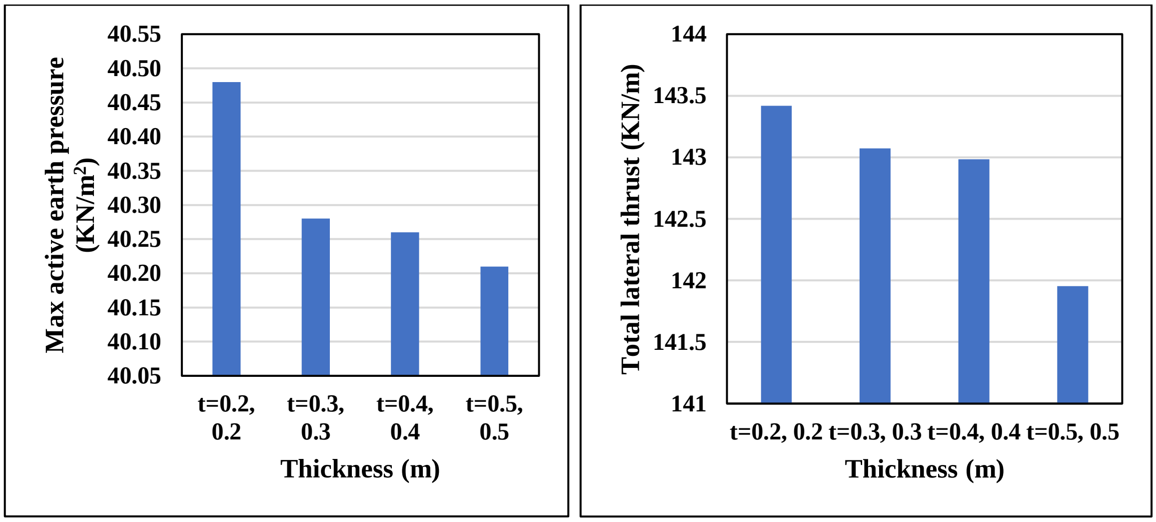


Figure 4.41. Active earth pressure distribution for different thicknesses of relief shelves for two relief shelves

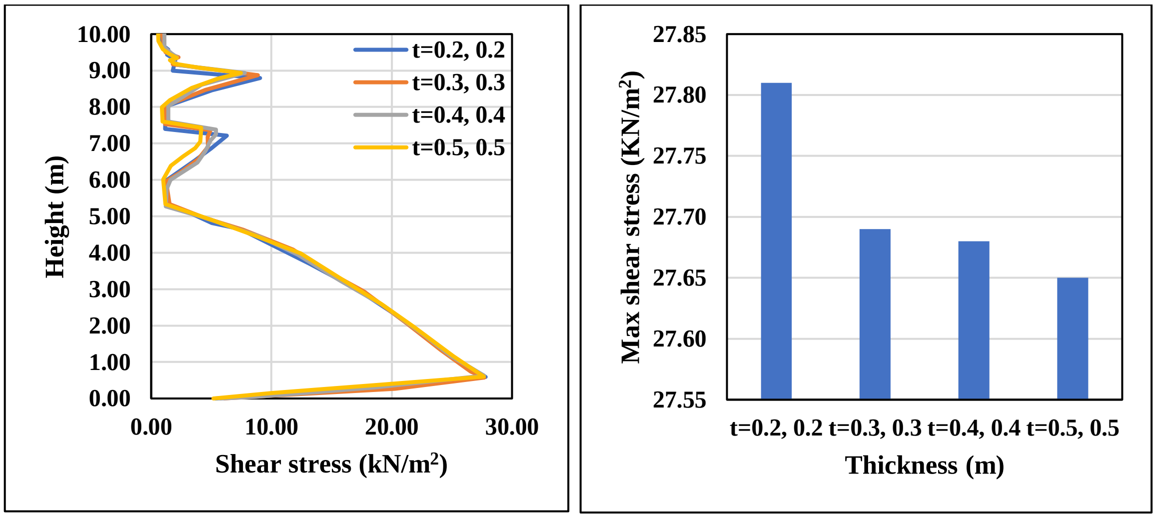


(a) (b)

Figure 4.42. Variation of (a). maximum earth pressure and (b) lateral thrust on the wall with a thickness of relief shelves for two relief shelves

4.4.3.2. Shear stress (S)

Not much difference was observed in shear stresses were observed by changing the thickness of the shelves, but nevertheless, it was decreased as the shelf thicknesses were increased by a small number (Figure 4.43).

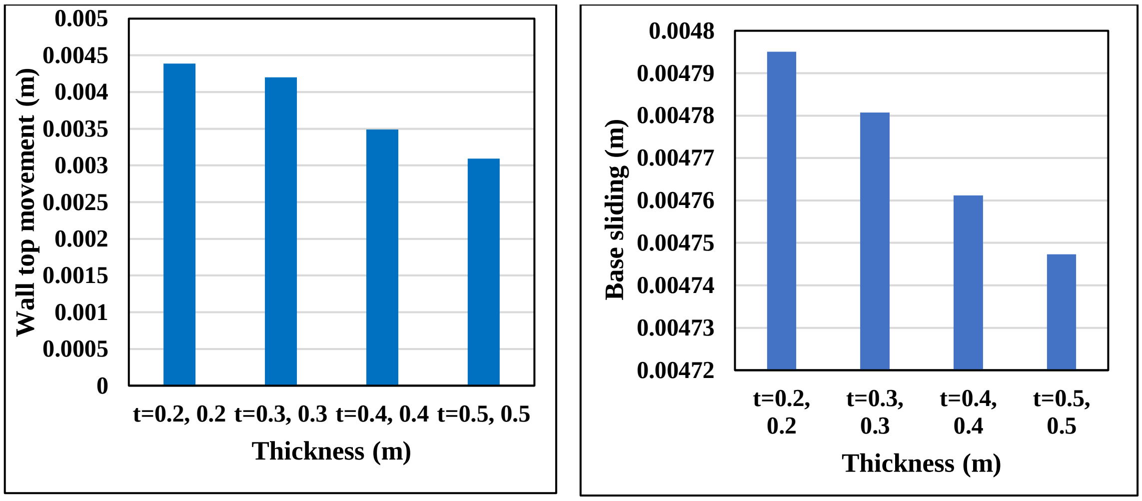


(a) (b)

Figure 4.43. (a). Shear stress along the wall for different thicknesses and (b). Variation of maximum shear stress with thicknesses of relief shelves for two relief shelves

4.4.3.3. Wall top movement (D_T) and base sliding (D_S)

Similar to retaining wall with a single shelf, both wall top movement and base sliding of the retaining wall was reduced by a small value when thicknesses of both the shelves were increased from 0.2m to 0.5m (Figure 4.44).



(a) (b)

Figure 4.44. Variation of (a). wall top movement and (b). base sliding with thicknesses of relief shelves for two relief shelves

4.4.3.4. Bending moment (M)

Bending moment diagrams for different thicknesses of the shelves were also very similar to each other (Figure 4.45). With a very small difference, the positive bending moment along the wall as reduced from 286.72 kNm to 266.52 kNm with an increase in the thickness of both the shelves from 0.2m to 0.5m, respectively (Figure 4.46).

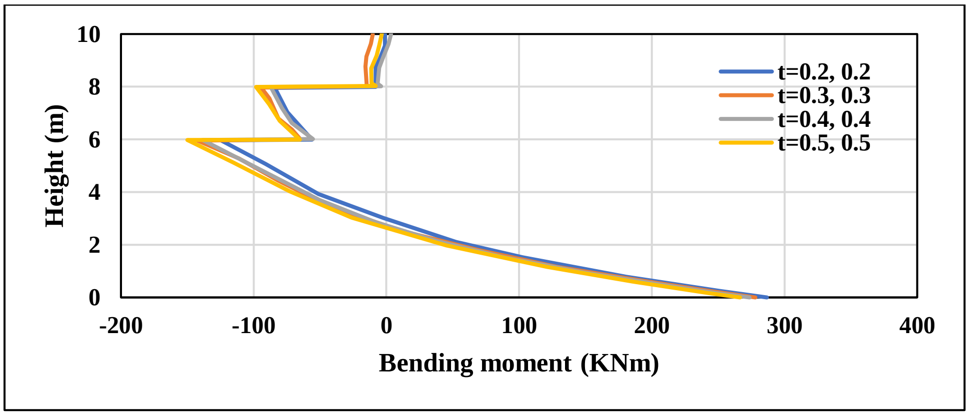
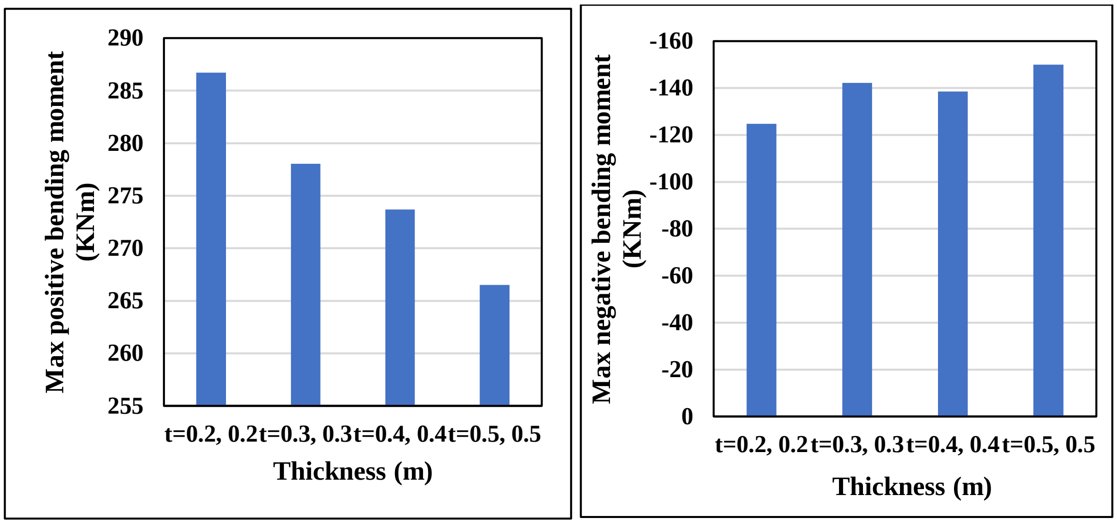


Figure 4.45. Bending moment along the wall for different thicknesses of relief shelves for two relief shelves



(a) (b)

Figure 4.46. Variation of (a). maximum positive and (b). maximum negative bending moment along the wall with thicknesses of relief shelves for two relief shelves

4.4.4. Best combination of parameters in case of two relief shelves

After analyzing the influence of each of the parameters of both the relief shelves on the stability of retaining wall, the best combination of parameters is found to be the one when location factors of 0.3 and 0.6, along with width factor and thickness of 0.15 and 0.5 m for both the shelves were used, as it produced better results among all the models analyzed within the scope of the present study. In the described case, maximum active earth pressure and total lateral thrust on the wall of 34.93 kN/m^2 and 133.25 kN/m were produced respectively, which produced the overturning moment of 249.64 kNm (34.34 percent less than that of the simple wall without shelf) and maximum shear stress of 25.19 kN/m^2. Moreover, wall top movement was reduced from 0.01824 m in case of a simple wall to 0.00271 m, along with a significant reduction in base sliding from 0.00679 m to 0.00464 m. For this combination, the factor of safety against sliding and overturning were also estimated which were found to be improved significantly from 1.52 to 2.37 and 1.15 to 2.15, respectively. The improvement in the stability results is illustrated in Table 4.2 below.

Table 4.2. Effect of optimum parameters of two relief shelves on the stability of retaining wall

S. No	Result	Reduction	Increase
1	Maximum active earth pressure (kN/m^2)	28.52 %	-
2	Lateral thrust (kN/m)	24.34 %	-
3	Shear stress (kN/m^2)	22.25 %	-
4	Wall top movement (m)	85.14 %	-
5	Base sliding (m)	31.66 %	-
6	Overturning bending moment (kNm)	34.34 %	-
7	Factor of safety against overturning	-	51.47 %
8	Factor of safety against sliding	-	28.97 %

4.5. Comparative analysis of all types of retaining wall in the present study

Three kinds of retaining walls have been analyzed in the present study, which is retaining wall without, single, and two relief shelves. When retaining wall without any shelf is compared to the walls with single and two relief shelves, it is found that total lateral thrust is reduced by 16.58 % and 24.34 % in cases of single and two shelves, respectively. These reductions enhanced the stability of retaining wall in terms of base sliding and wall top movement, by improving factor of safety against sliding ($FOS_{sliding}$) from 1.52 to 1.92 and 2.15 for single and two shelves, respectively, along with improvement in the factor of safety against overturning ($FOS_{overturning}$) from 1.15 to 2.58 and 2.37 for single and two shelves, respectively.

Analysis of the effect of single and two relief shelves by varying their parameter's dimensions and observing the corresponding changes in the stability of retaining wall has shown that the provision of shelves has enhanced the stability of retaining wall in both the cases of single and two relief shelves. The optimum parameters for both the cases have been discussed in Section 4.3.4 and Section 4.4.4, which shows improvements in both $FOS_{sliding}$ and $FOS_{overturning}$. $FOS_{sliding}$ in the case of two relief shelves is found to be greater than that of a single shelf, which was because of lesser total lateral thrust in the former case. On the other hand, $FOS_{overturning}$ in case of two relief shelves is found to be less than that of the single shelf, which according to the author's understanding is because, in case of the single shelf, the width factor used was 0.2, while for the two shelves, lesser width factor of 0.15 was used for both the shelves. Therefore, due to lesser width factors, the shelves couldn't hold the away movement of the stem from backfill, as compared to the single shelf of greater width factor did. Hence, in the case of two shelves, the wall top movement along with $FOS_{overturning}$ is found to be a little less than those of a single shelf.

4.6. Limitations of the present research

Some limitations observed by the author in the present study include lack of small and full-scale physical testing, settling down of soil beneath the shelf, and development of tension zones at the locations of relief shelves. Soil settlement will not allow the soil beneath the shelf to support it; therefore, proper attention on the design of the shelf must be given. Moreover, water can accumulate in tension crack zones, exerting hydraulic stresses; therefore, the proper drainage system should be employed so that water is not in any case allowed to stay there.

Chapter. 5

5. SUMMARY & CONCLUSION

5.1. Summary

The present study addresses the influence and effectiveness of relief shelves on the stability of retaining wall with cohesive soil as backfill. This technique of enhancing the stability of the retaining wall may prove economical if properly implemented. The conclusions drawn are discussed in the section below.

5.2. Conclusion

The present study addresses the influence and effectiveness of relief shelves on the stability of retaining wall with cohesive soil as backfill. This technique of enhancing the stability of the retaining wall may prove economical if properly implemented. Following conclusions have been drawn from the study:

i. Among all the cases studied for retaining wall with a single relief shelf, the best possible location factor of a single relief shelf was found to be 0.4 with a width factor of 0.2 and thickness 0.5 m.
ii. Provision of relief shelf has found to reduce active earth pressure, lateral thrust, shear stress, top wall movement, base sliding, and positive bending moment on the wall up to 23.83 percent, 16.58 percent, 21.79 percent, 114.98 percent, 28.57 percent, and 36.05 percent for single relief shelf, respectively.
iii. Among all the cases considered for retaining wall with two relief shelves, location factors of 0.3 and 0.6, along with width factor 0.2 and thickness 0.5 m were found to be the ones to obtain optimum stability.
iv. Provision of relief shelves has found to reduce active earth pressure, lateral thrust, shear stress, top wall movement, base sliding, and positive bending moment on the wall up to 28.52 percent, 24.34 percent, 22.25 percent, 85.14 percent, 31.66 percent, and 34.34 percent for two relief shelves, respectively.

v. At the location of the relief shelf, the active earth pressure was observed to be higher than the simple cantilever wall, but ultimately the peak active stress, as well as lateral thrust on the wall, were reduced.

vi. It was observed that for relief shelves of smaller width had no or little adverse effect on the stability of retaining wall, but as the width was increased, then it improved the stability of the wall. The top wall movement and base sliding were increased by the provision of relief shelf of width factor 0.05, but as it was increased both base sliding and top wall movement were significantly reduced. So, it is not recommended to use relief shelves of a comparatively very smaller width.

vii. The thickness of the relief shelf was varied from 0.2 m to 0.5 m and a very small amount of change was observed in results by varying it. But still, it's not recommended to use a smaller thickness of shelves as they could break and cause the failure of the wall.

viii. The tension was found at every location where the relief shelf was attached, for which proper remediation should be employed.

5.3. Future recommendations

i. The performance of retaining wall with relief shelves should be analyzed under dynamic or seismic loading conditions.

ii. Analyses on the same type of retaining wall can be conducted using different material models.

iii. Full-scale model testing on these types of walls is highly recommended.

iv. The performance of these types of retaining walls must be studied with different levels of the water tables.

Chapter. 6

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