Comparative Analysis and Behavior of Cantilever Retaining Wall with and Without Relief Shelves

Mandira Faldesai and P. Savoikar

Abstract Retaining walls are an essential part of almost all infrastructure projects, to support vertical backfills. There are various ways of constructing a retaining wall. Retaining wall with relief shelves is one of the subset of cantilever retaining walls. A retaining wall with pressure relief shelves decreases the active lateral earth pressure and increases the overall stability of the retaining wall. As a result of reduced earth pressure, the thickness of stem also gets reduced which results in to an economic design. The present study aims at comprehending the performance of such walls and to discover the effectiveness of these walls to reduce earth pressure. The influence of factors like the location of the shelf and stiffness of shelf, shelf width, etc., on the behavior of the retaining wall is also studied. This work presents a thorough comparative analysis of RCC cantilever retaining walls with (i) no shelves. (ii) single shelf. (iii) two shelves. (iv) three shelves (v) four shelves, with finding out the best location for providing shelves.

Keywords Cantilever retaining walls · Relief shelf · Lateral pressure · Overall stability

1 Introduction

Lateral earth pressure on retaining walls is the major factor which influences the sectional dimensions of the wall. If the height of soil retained is large, the retaining walls are required to resist larger lateral earth pressure and in such cases the reinforced soil walls are found to be a possible solution. But for construction of such walls, a well graded granular material is preferable due to its higher shear resistance and good soil reinforcement interaction hence availability of a suitable backfill material is the main criteria. Thus, to tackle such issues the lateral thrust on the wall should be

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reduced, which would apparently reduce the sectional dimensions of the wall and cost of the project. There are many ways to reduce the lateral earth pressure such as use of Geo-inclusion, light weight backfill, etc. Providing a relief shelves connected to the stem of the cantilever retaining wall can reduce the earth pressure and are considered to be the special case of retaining walls [1]. The relief shelves are provided on the retained side of the retaining wall. These shelves break the total retained height in to smaller heights of stem which results in reduction of soil pressure on the stem. As a result of this, the thickness of stem reduces which results into an economical design there is less use of reinforcement in the wall cross section [1]. Relieving shelves are horizontal slabs incorporated in the stems of R. C. cantilever retaining walls, with the objective of providing partial relief of the active earth pressure acting on the stem. Number of such shelves is constructed at regular spacing along the height of the wall. Kurian [2] explains the contribution of the relieving shelf to the stability of the retaining wall and to the reduction of the stem thickness due to the reduction in earth pressure, besides examining the scope of overall economy from a cost- benefit angle.

Jumikis [3] presented the effect of provision of relief shelves on the earth pressure and noted that extending them beyond the rupture surface in the backfill can significantly reduce the lateral earth pressure and increase the stability of retaining wall. Klein [4] reported a distribution for the earth pressure above and under the shelf which was observed to be in line with the results obtained by [5]. It was concluded that solution of [4] was in good agreement with the results of the FEM and while Jumikis's solution (1964) was not. Chaudhuri [6] reported that wall with relief shelf can retain larger height of sand just prior to the emerging overturning compared to wall without relief shelf. Yakovlev [5] concluded that for the same embedded depths of a shelf, the dimensions of the sliding zone increases with increasing platform width. Phatak [7] presented experimental study on flexible cantilever wall with relief shelf to show extensive reduction in earth pressure. Phatak [7] corrected an error in Raychaudhuri's solution. Bowles [8] recommended such walls as a likely solution for high retaining walls, while alerting that the soil must be satisfactorily compacted up to relief shelf. Raychaudhuri [9] studied the influence of the relief shelf by deducting the weight of the soil above the shelf from the failure wedge; though the change in the center of gravity for the wedge was not considered. Bell [10] in his Ground Engineer's book, assumed that there is a transition zone under the shelf and after this zone the earth returns to its original distribution; i.e., to the distribution of the cantilever retaining wall.

Padhye and Ullagaddi [11] reported that active earth pressure and lever arm are considerably reduced due to provision of shelf and there by achieves a considerable reduction in the moment about the base. Liu and Lin [12] recommended a mathematical model to calculate the earth pressure for different shelf widths. It was recommended that the distribution of the earth pressure starts at zero under the shelf and increases linearly with depth. For short shelves, an additional rupture surface starting from the end of the shelf and running parallel to the global rupture line was recommended. It was reported that the FEM has limitations and that the other methods are in good agreement with each other. Liu et al. [13] reported that when the depth of relief shelf exceeds a certain value, active earth pressure on the upper wall was not reduced significantly. The width of relief shelf has a strong influence on earth pressure near the surface of relief shelf, but not much effect was found on the overall distribution of earth pressure on upper wall. Liu et al. [14] conducted model study of pile-supported cantilever retaining wall with single relief shelf and demonstrated that the earth pressure is zero below the relief shelf. Cantilever retaining walls with relief shelves is one of the special case of retaining walls [1]. Providing relief shelves on the soil retained side, decreases the total active earth pressure on the wall, which results in reducing the thickness of the wall resulting in to an economic design due to use of less reinforcement on wall horizontal cross section on the level of contraction joints [1]. Hany [1] studied the influence of number of shelves on the earth pressure acting on the wall. The shelves work on decreasing the maximum bending moment and the top movement of the wall significantly. It was reported that the provision of a single shelf at the height of 0.3 H results in reduction of bending moments by about 30% as compared to a retaining wall without shelves. The shelf width is recommended to be extended after the rupture surface with thickness ratio ($t_s/b = 0.10$).

2 Influence of Shelves on Active Earth Pressure Distribution

Figure 1 shows the effect of providing relieving shelf on distribution of earth pressure behind the retaining wall.

In the present study, the analysis of cantilever retaining wall with pressure relief shelves is done to optimize the number and the best location of shelves.

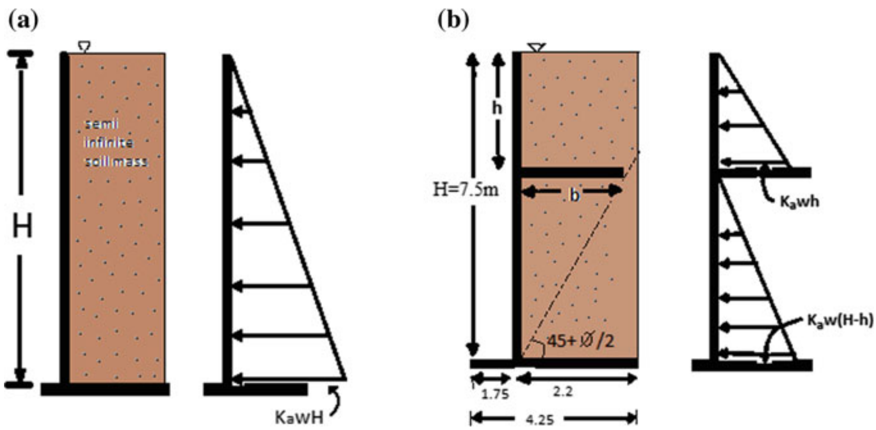

Fig. 1 Pressure distribution on stem **a** without shelf **b** with shelf

Fig. 2 Ambaji–Fatorda, Goa Landslide site

Table 1 Geotechnical properties of the soil at the site

Site	Grain size analysis			Spec. gravity	Dry density kN/m^3	Liquid limit %	Plastic limit %	PI
	Gravel content (%)	Sand content (%)	Silt and clay content (%)					
Ambaji	28.06	65.61	6.33	2.66	15.3	41	21	20

3 Methodology

A retaining wall relief shelf is designed for a slope at Ambaji–Fatorda, Margao Goa. The site is located South Goa Collectorate building at Margao Goa. The site had a steep slope covered with medium to dense vegetation. Landslide had occurred due to flowing down of debris during rains (Fig. 2).

Parametric studies were carried out. Height of slope is 13.8 m and inclination of slope is 71.60°. Geotechnical investigation for the site is given in Table 1.

4 Analysis of Cases

Analysis of cantilever retaining wall with and without relief shelf is done on the slope at Ambajim Margao site. STAAD Pro V8i software was used for analysis. The following analytical models are analyzed and designed for cantilever retaining wall with: (1) Case 1: no shelves (CWNS), (2) Case 2: with one shelf (CWOS), (3) Case 3: with two shelves (CWTS) and (4) Case 4: with three shelves (CWThS). (5) Case 5: with four shelves (CWFS). Each model is designed using same data for the study. Assumed and calculated data are given in Table 2.

Table 2 Assumed data for all models

Sr. No.	Description	Details
1	Height of retaining wall, H	13.8 m
2	Unit weight of soil, γ	17.2 kN/m^3
3	Cohesion of backfill soil, c	8 kN/m^2
4	Safe bearing capacity of soil, q_s	200 kN/m^2
5	Internal friction angle of soil, ϕ	28.3°
6	Coeff. of friction bet concrete and soil, μ	0.5
7	Inclination of slope	71.60°
8	Grade of concrete	M35
9	Grade of steel	Fe415
10	Depth of foundation	1.5 m
11	Coefficient of active earth pressure	0.356
12	Thickness of base slab	1.3 m
13	Width of base slab	7.5 m
14	Toe projection	2 m
15	Thickness of stem at the base	1.5 m
16	Thickness at the top	0.5 m
17 18	Height of stem Heel projection	14 m 4 m

4.1 Analysis of CWNS

The analysis of the cantilever retaining wall with no shelf (CWNS) is shown in Fig. 3a and its pressure distribution is shown in Fig. 3b. The bending moment diagram (BMD)

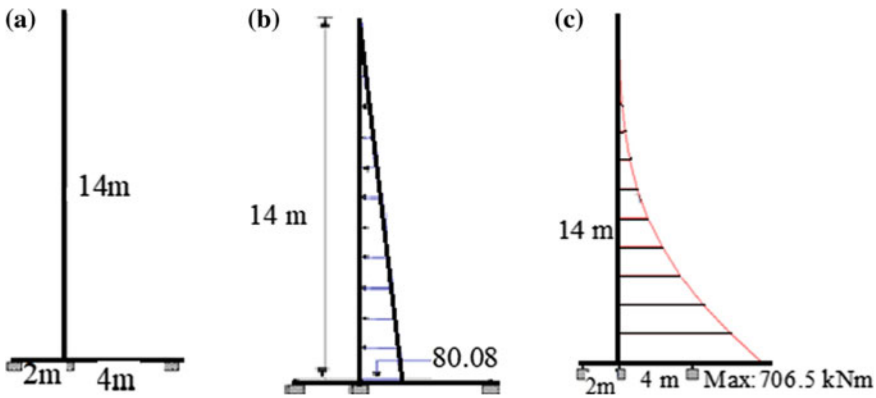

Fig. 3 **a** Analysis of retaining wall without shelf, **b** Lateral pressure distribution diagram, **c** BMD from STAAD Pro Software

Table 3 Bending moment details for CWNS

BM at the base of the stem at 14 m	Area of BMD
760.5 kN-m	2661.175 kNm^2

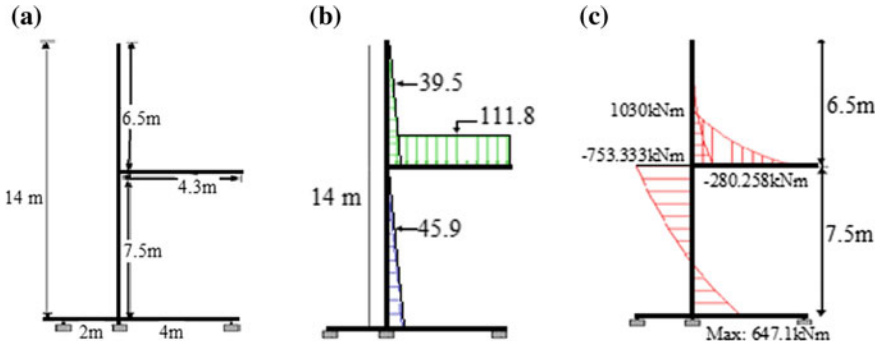

Fig. 4 **a** Analysis of retaining wall with one shelf, **b** Pressure distribution diagram, **c** BMD from STAAD Pro Software

for the stem obtained from STAAD Pro software is shown in Fig. 3c. The results are given in Table 3.

4.2 *Analysis of CWOS*

The analysis of cantilever retaining wall with single shelf for a retained height of 14 m is worked out. Position of shelf is varied from H/28 to 27H/28, measured from top of the stem. Lateral soil pressure is calculated for the various cases and from which area of BMD is estimated. The model of cantilever retaining wall with one shelf is shown in Fig. 4a and its pressure distribution is shown in Fig. 4b. BMD of CWOS from STAAD Pro is shown in Fig. 4c. The values achieved from the analysis are given below in Table 4.

BMD for different possible shelf height is obtained and the area of BMD is calculated from which the least value is selected as the optimum height for shelf. For cantilever with one shelf the optimum position for shelf is found to be 13H/28 i.e. 6.5 m height from the top of the stem.

4.3 *Analysis of CWTS*

The analysis of cantilever wall with two shelves is done for various locations of shelf. The choice of position of top shelf is of range H/28 to 26H/28 and that of bottom shelf is from 2H/28 to 27H/28 considered from top of stem and area of BMD is computed.

Table 4 BMD areas for various shelf positions for CWOS

Location of shelf from top of stem	Area of BMD (kNm^2)
H/28	2936.53
2H/28	3254.7
3H/28	2695.2
4H/28	2508.1
5H/28	1262.815
6H/28	−1164.2
7H/28	−1028.175
8H/28	−863.63
9H/28	−802.5
10H/28	3259.5
11H/28	3304.56
12H/28	3755.5
13H/28	**1276.5**
14H/28	1707.517
15H/28	1753.65
16H/28	1896.3
17H/28	2759.3
18H/28	1942.6
19H/28	1802.54
20H/28	2168.54
21H/28	2463.25
22H/28	2683.78
23H/28	2546.36
24H/28	2741.12
25H/28	2896.35
26H/28	3689.56
27H/28	3726.14

The model of cantilever retaining wall with two shelves is shown in Fig. 5a and its pressure distribution is shown in Fig. 5b. The BMD of the cantilever wall with two shelves from STAAD Pro is shown in Fig. 5c. The values gained from the analysis for the most a precise position of shelves is given in Table 5.

4.4 Analysis of CWThS

The analysis of CWThS for height of 14 m is done for different location of shelf. The series of position of upper shelf is H/28 to 25H/28 and that of middle shelf is from

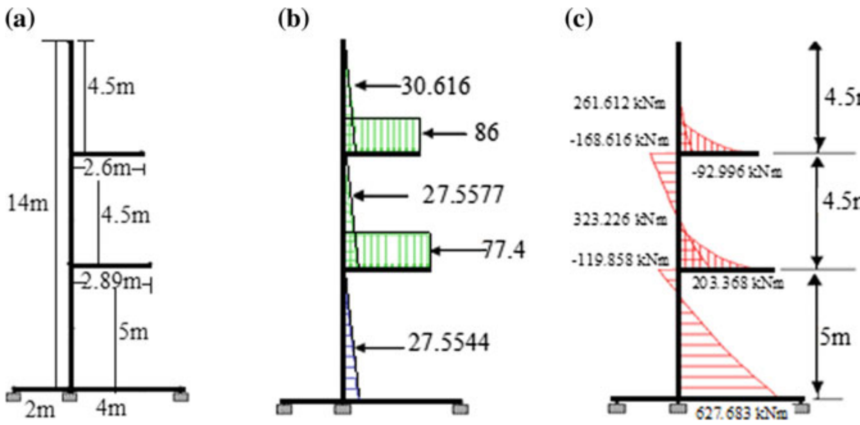

Fig. 5 **a** Analysis of retaining wall with two shelves, **b** Pressure distribution diagram, **c** BMD from STAAD Pro Software

Table 5 BMD details for CWTS

Depiction	Location of shelves from top of stem, 1st shelf at 5H/15 and 2nd shelf at 10H/15
BM at joint 5 due to soil weight above 1st shelf	261.612 kN-m
BM at joint 5	−92.996 kN-m
BM just below point 5	−168.616 kN-m
BM at point 3 just above 2nd shelf	323.226 kN-m
BM at point 3	203.368 kN-m
BM just below point 3	−119.858 kN-m
BM at point 1	627.683 kN-m
Area of BMD	963.38 kNm^2

2H/28 to 26H/28 and for lower shelf is from 3H/28 to 27H/28 measured from top of stem and its area of BMD is computed. The model of cantilever retaining wall with three shelves is shown in Fig. 6a. Pressure distribution of the stem of CWSS is shown in Fig. 6b. BMD of CWTS from STAAD Pro is shown in Fig. 6c. The values attained from the analysis for the most a precise position of shelves is given in Table 6.

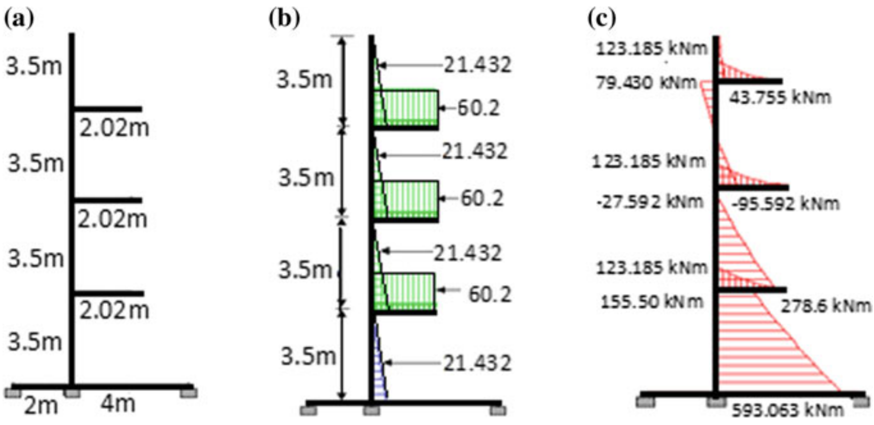

Fig. 6 **a** Analysis of retaining wall with three shelves, **b** Pressure distribution diagram, **c** BMD from STAAD Pro Software

Table 6 BMD details for CWThS

Depiction	Location of shelves from top of stem, 1st shelf at 7H/28; 2nd shelf at 14H/28; 3rd shelf at 21H/28
BM at point 7 due to soil weight above 1st shelf	123.185 kN-m
BM at point 7	43.755 kN-m
BM just below point 7	79.430 kN-m
BM at point 5 just above 2nd shelf	123.185 kN-m
BM at point 5	−95.592 kN-m
BM just below point 5	−27.592 kN-m
BM at point 3 due to soil wt above 3rd shelf	123.185 kN-m
BM at point 3	278.6 kN-m
BM just below point 3	155.509 kN-m
BM at point1	593.063 kN-m
Area of BMD	724.917 k-Nm^2

4.5 Analysis of CWFS

The analysis of CWFS for height of 14 m is done for different location of shelf. The series of position of upper shelf is H/28 to 24H/28 and that of second shelf from top is from 2H/28 to 25H/28 and for third shelf is from 3H/28 to 26H/28 and forth shelf that is the lower shelf is from 4 h/28 to 27 h/28 measured from top of stem and its

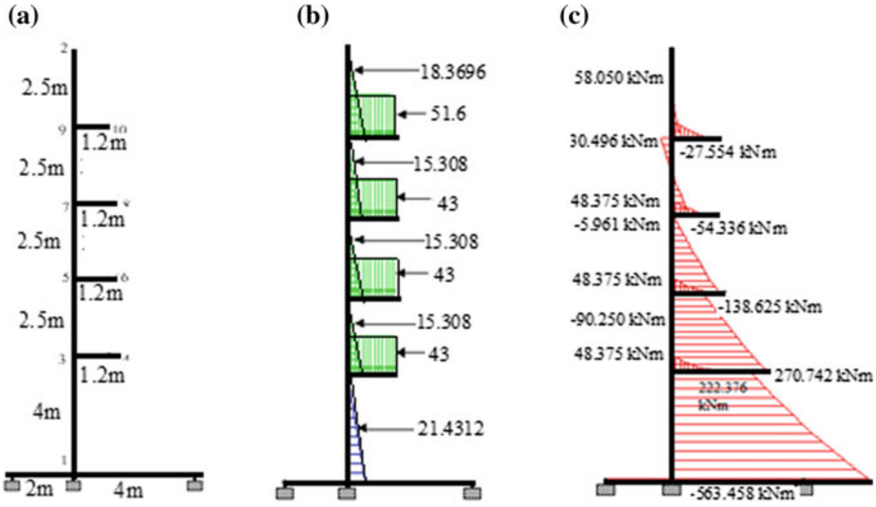

Fig. 7 **a** Analysis of retaining wall with three shelves, **b** Pressure distribution diagram, **c** BMD from STAAD Pro Software

area of BMD is computed. The model of cantilever retaining wall with three shelves is shown in Fig. 7a. Pressure distribution of the stem of CWSS is shown in Fig. 7b. BMD of CWTS from STAAD Pro is shown in Fig. 7c. The values attained from the analysis for the most a precise position of shelves is given in Table 7.

5 Results

From the analysis of CWNS, CWOS, CWTS, CWThS, and CWFS for different shelf positions the results are found (Table 8).

6 Lateral Displacement of Retaining Walls

Lateral displacement of the wall away from backfill is studied and shown in Fig. 8. It can be seen that provision of relief shelves to the wall has marginally reduced the maximum lateral displacement of the wall from 30.4 mm (wall without relief shelf) to 23 mm (walls with relief shelf). Provision of shelf reduces the total thrust on the wall and hence weight of wall increases which reduces the maximum displacement.

Table 7 BMD details for CWFS

Depiction	Location of shelves from top of stem, 1st shelf at 6H/28; 2nd shelf at 11H/28; 3rd shelf at 16H/28; 4th shelf at 21H/28
BM at point 9 due to soil weight above 1st shelf BM at point 9 BM just below point 9 BM at point 7 due to soil wt above 2nd shelf	58.050 kN-m −27.554 kN-m 30.496 kN-m 48.375 kN-m
BM at point 7	−54.336 kN-m
BM just below point 7	−5.961 kN-m
BM at point 5 just above 3rd shelf	48.375 kN-m
BM at point 5	−138.625 kN-m
BM just below point 5	−90.250 kN-m
BM at point 3 due to soil wt above 4th shelf	48.375 kN-m
BM at point 3	270.742 kN-m
BM just below point 3	222.376 kN-m
BM at point 1	−563.458 kN-m
Area of BMD	615.375 k Nm^2

Table 8 Comparison between different cantilever walls

Quantities	Model 1: CWNS	Model 2: CWOS	Model 3: CWTS	Model 4: CWThS	Model 5: CWFS
BMD Area ($kN\text{-}m^2$)	2661.175	1276.5	963.38	724.286	615.375
Economic shelf location	–	13H/28	8H/28-upper 18H/28-lower	7H/28-upper 14H/28-middle 21H/28-lower	6H/28-1st 11H/28-2nd 16H/28-3rd 21H/28-4th
Reduction in thrust in %	–	14.91	17.46	22.01	25.90
Steel in tonnes	17.01	14.34	12.54	12.32	12.01
Comparison of steel with Model 1	–	15.81%	26.27%	27.57	29.39%

7 Influence of Thickness and Length of Shelves

The shelf inflexibility “stiffness” is affected by the shelf width and its thickness. For stability, shelf should be extended beyond rupture surface. It is observed that shelves reduce the lateral earth pressure and thereby the maximum moment acting on the wall. It is also observed that the maximum bending moment and deflection of the

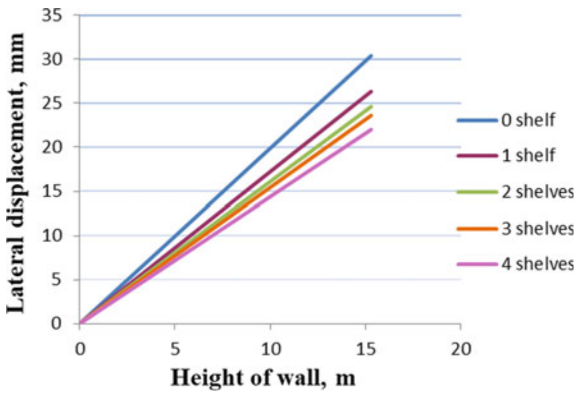

Fig. 8 Lateral displacement of retaining wall with relief shelves

top of the stem is also influenced by the position of the shelves. One of the important criterions to be considered while providing relief shelf on the cantilever wall is the deflection of relief shelves. A comparison of deflection outlines of relief shelves with differing width and thickness are produced below in Fig. 9a, b. In the first case length of shelf (measured perpendicular to the stem wall) of retaining wall is varied from 0.5 to 1.5 m and deflection is noted. Retaining wall with one shelf with the best shelf positions i.e. 13H/28 is used for this case. The influence of shelf length on BMD and deflection is studied by keeping thickness of shelf constant, equal to 0.3 m. In the next case, the shelf length is kept constant equal to 1.2 m and shelf thickness is varied from 0.2 m to 0.5 m, keeping shelf position at 13H/28 from the top of the stem.

It is seen from Fig. 9a, that maximum deflection of relief shelves increases with the length of the shelf. As the length of the shelf increases, the deflection also increases. This reduces the total thrust on the wall due to the increased weight of the wall. There exists a sure value beyond which the length of the relief shelf cannot be increased as greater length results in large deflection which leads to excessive backfill settlement which in turn affects the durability of the neighboring structures. This study would limit maximum length of relief shelves to 1.2 m. As greater length of shelves lead

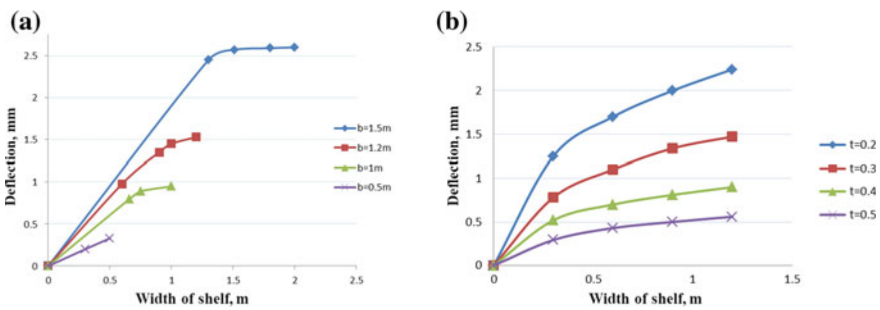

Fig. 9 Deflection profile of relief shelves **a** with different widths **b** with different thickness

Table 9 Maximum deflection (mm) of relief shelves for various retaining walls

Relief shelf	RS0.5	RS1	RS1.2	RS1.5
RS1	1.56	2.17	2.85	3.85
RS2	1.17	1.5	2.32	2.83
RS3	0.95	1.43	1.71	2.71
RS4	0.33	0.95	1.63	2.60

to extreme deflection due to its own weight, this can increase further due to creep. Amongst all the cases of retaining wall with relief shelf, the shelf with length of 1.2 m delivers highest benefit, not leading to unnecessary deflection of shelves. From Fig. 9b, it is observed that defection of shelves is reduced with increase in thickness of the shelf. The lesser thickness shelf tends to deflect more than the larger one. This deflection tends to make the shelf rest on the beneath soil which results in increase of the vertical stresses on the soil, thus leading to increase the lateral earth pressure on the wall below the shelf. In this case the prominent thickness amongst all the cases of retaining wall with relief shelf is shelf of thickness 0.3 m. From Fig. 9a, b, it is credited to the fact that relief shelves perform similar to cantilever beams having uniform distributed loading. As the deflection of cantilever beam with uniform distributed loading is relative to the forth power of length of cantilever beam and inversely proportional to moment if inertia (Table 9).

7.1 Deflection of Relief Shelves

Deflection of shelves from top to bottom are observed and compared. Deflection at different shelf position are noted and given in Table 10. RS1, RS2, RS3 and RS4 represent the relief shelves from upper to lower retaining wall. RS0.5, RS1, RS1.2 and RS1.5 represent the width of relief shelf.

It can be seen that the deflection of relief shelves from top to bottom of wall decreases and is found to be minimum for the lowest shelf, for all retaining walls with relief shelves. However, it was observed that the deflection of relief shelves significantly increases when length of the shelf is 1.5 m. Hence, the maximum length of relief shelf is to be restricted to 1.2 m.

8 Conclusions

The study involves thorough analysis using STAAD Pro software to assess the efficiency of providing relief shelves to the retaining walls.

It is seen that retaining walls with shelves are efficient in comparison to cantilever retaining wall with without shelves. Based on the present study, it can be concluded that

1. In the case of cantilever retaining wall with single shelf, the optimized location is at 13H/28 from top of the stem, while for retaining wall with two shelves, the optimized location of shelves is 9H/28 and 18H/28 where H is the height of stem, measured from top of the wall.
2. In the case of retaining wall with three shelves, the optimized position of shelves are 7H/28, 17H/28, and 21H/28 respectively, measured from top of the wall.
3. In the case of retaining wall with four shelves, the optimized position of shelves are 6H/28, 11H/28, 16H/28, and 21H/28 respectively, measured from top of the wall.
4. Provision of two shelves is economical proposition than single shelf, while three shelves are further economical than two shelves.
5. Maximum deflection of relief shelves are increased with the width of the relief shelf and decreased with increase in thickness of the shelf.
6. It can be concluded that providing four shelves at economic locations i.e. 6H/28(upper), 11H/28, 16H/28, and 21H/28 of shelf thickness 0.3 m and shelf width 1.2 m will give the greatest serviceability and efficiency making the wall much safer in bearing capacity failure mode.

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