Effect of Relief Shelves on Cantilever Retaining Walls

Preethi Sekar, Satya Kiran Raju Alluri and S. Suganya

Abstract Retaining walls are a part of everyday infrastructure, from retaining soil in mountain slopes to harbor structures. With the expectation to retain higher backfills, new and improved design methodologies, such as reinforced retaining wall, lightweight backfilling, are being implemented. A new method of construction consisting of relief shelves attached to the backfill side of the stem provides relief to the lateral pressure acting on the wall, thus reducing the overturning moment of the wall during stability analysis. Available literature suggests the use of retaining wall with shelf/shelves with experimental and theoretical computations based on provision of one or two shelves. The effect of using more than two shelves has not been studied extensively. This paper studies the effect of multiple shelves have on the lateral earth pressure acting on the stem. A parametric study was carried out to understand the variation of lateral earth pressure with the change in length and number of shelves at the back of the retaining wall. It is observed that the increase in number of shelves corresponds to reduction in total thrust and moment of the lateral earth pressure in comparison with that of single shelved retaining walls. It is also observed that short multi-shelved walls are much more efficient compared to long single shelved retaining walls of the same shelf length.

Keywords Special retaining structures · Lateral earth pressure · Relief shelves · FEM

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1 Introduction

Retaining walls are an integral part of retaining any vertical column of soil. For retaining walls less than 6 m, generally cantilever retaining walls are utilized while, for retaining walls greater than 6 m, counterfort retaining walls are used. However, with the development of infrastructure and space constraints, higher retaining structures are desired with less access to backfill area. Reduction in the lateral earth pressure can lead to an economical design. Reinforced retaining walls, geo-inclusion, lightweight backfilling and relief shelves are some of the methods adopted to relieve some of the lateral pressure on the stem of the retaining wall.

Relief shelves are horizontal cantilever beams constructed monolithically with the stem of the retaining wall along the length of the wall. However, limited theoretical knowledge of this methodology leads to failure of the retaining wall in many cases. The failure may include localized passive pressure on the stem leading to tension failure just below the shelf as seen in a location in Hyderabad [1–3]. They may also face other problems like wedge formation away from the relief shelves leading to a further complication of the design of retaining wall [4].

Though few structures have been constructed, the mechanism behind stress reduction has not been well documented due to its complexity and variability based on the uncertainties that develop due to the introduction of relief shelves. Few literature also demerits the use of shelves in retaining wall. The present study aims at understanding the theory of the relief shelves, their positioning and the desired number of shelves to be provided.

2 Literature Review

One of the earliest studies on retaining walls with relief shelves was carried out by Jumikis [5] where a study was carried out to assess the effect of introduction of relief shelves on the stability of the retaining structure. He theoretically established the lateral earth pressure for a counterfort retaining wall with two relief shelves. His study also concluded that there is a reduction in the lateral earth pressure of the soil on the wall if the shelf is extended to the rupture plane of the soil. Yakovlev [6–10] has extensively studied the effect of a single and two shelves on various factors. He concluded that if the wall is allowed to displace, an internal sliding surface is created from the backfill zone above the shelf. By introducing a shelf intercepting this sliding surface, a new surface is created originating from shelf above, thus reducing the lateral pressure on the wall.

Raychaudhuri [11] determined the reduction factors for the decrease in lateral earth pressure, due to the introduction of a shelf, on the backfill using Coulomb's theory and provided charts for the same. Phatak and Patil [12] derived the theoretical concept for computing earth pressure using Rankine's theory. They calculated the earth pressure distribution based on the shift of center of gravity of the backfill material above the shelf and summarized that shelves reduce the active earth pressure. Shehata [13] summarized that using Mohr–Coulomb model may actually increase the lateral earth's pressure in cases of staged construction during the loading–unloading activity and suggested that hardening soil model best represents the behavior of soil in retaining wall with shelves. He has also studied the effect of shelves on the earth pressure and concluded that shelves significantly decrease the lateral earth pressure. He also studied the effect of shelf rigidity and concluded that effective stiffness is desired for the shelves. He also concluded the previous assumptions from literature that for a significant effect of shelves, the shelves should extend into the rupture plane. Padhye and Ullagaddi [14] proposed reduction factors for retaining wall with two relief shelves theoretically using Coulomb's method for computation of lateral earth pressure.

Chauhan [1–3] conducted a numerical analysis using FLAC-3D on the effectiveness of relief shelf/shelves and concluded that the thrust on a rigid retaining wall significantly reduces in the presence of shelves for a single and double relief shelved retaining wall. They extended the study and analyzed the length of shelves on the lateral earth pressure for both cohesive and cohesionless backfills. A parametric study on the length of the relief shelves was carried out against the lateral earth pressure for equally spaced multiple shelves. They concluded that using larger lengths of the shelf might lead to unanticipated stresses on the stem instigating distress. They identified that the relief shelves are suitable and effective for even cohesive backfills. They also conducted experimental studies to determine the influence of width for rigid retaining wall with a surcharge and observed that the deflection in the relief shelf is proportional to the width of the shelf.

Klein [15] derived the theory for the earth pressure under and over the shelf/shelves and corrected the slope transition of earth pressure between shelves to be defined by the angle of internal friction, φ, which is more compatible with advanced soil models for finite element solutions as shown in Fig. 1.

3 Analytical Solution for Retaining Wall

Apart from the primitive solutions first derived based on Coulomb and Rankine's theory, a lot of modifications have been further introduced for the distribution of lateral earth pressure when relief shelf/shelves are considered. The shelved retaining wall works in the assumption that the shelf rests on a fully compacted soil and that the rigid connection between the shelf and stem. Of the theoretical models proposed for the distribution of lateral earth pressure on the stem, this paper utilizes Klein [15] model to analyze retaining wall with relief shelves if more than two relief shelves exist. It has already been established that extending the shelf into the rupture plane yields the maximum efficiency.

Therefore, this paper deals with shelves extruding into the rupture plane. Klein [15] model for a shelf intruding into the plane of rupture is as shown in Fig. 1. It can be seen that the lateral earth pressure near the base slab of the retaining wall remains

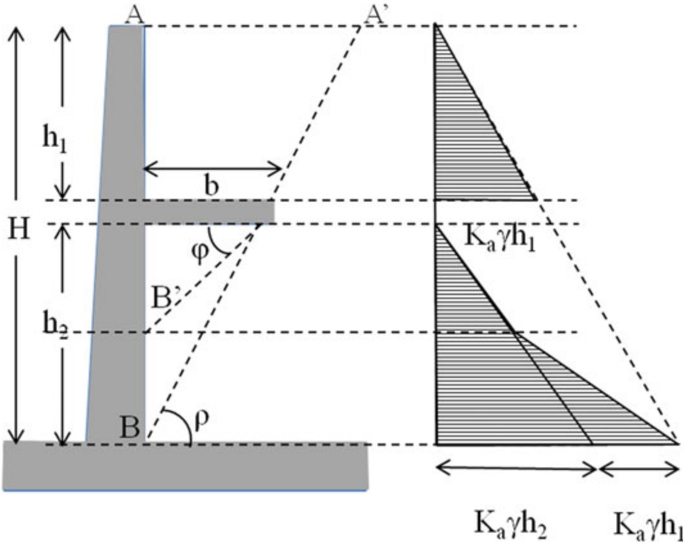

Fig. 1 Lateral earth pressure distribution. Adapted from Klein [15]

the same as that of a retaining wall without shelf. The same behavior is replicated for multi-shelved retaining wall as shown in Fig. 2. The shelf '*D*' will have a rupture plane *D*-*D*′ extending to the surface by an angle 'ρ' to the horizontal which is

$$\rho = 45^{\circ} + \frac{\varphi}{2} \tag{1}$$

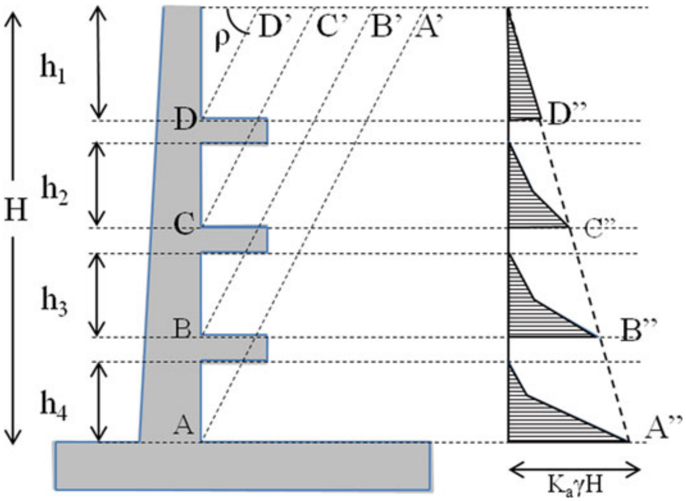

Fig. 2 Lateral earth pressure for multi-shelved retaining wall

The weight of soil just above the shelf 'D' produces a lateral earth pressure acting along height h_1. This weight gets transferred to the shelf, leading to zero lateral pressure just below the shelf. However, due to the change in center of gravity of the weight, an additional component of stress due to soil in h_1 acts in the section h_2. This additional component acts from a height where a plane made by 'φ' intersects the stem height from the bottom edge of the slab. Based on the above concept, the length of shelf needed for interfering with the rupture plane has been derived from

$$b = h \tan\left(45 - \frac{\varphi}{2}\right) \quad (2)$$

where b is the length of the shelf and h is the height of the shelf from the base.

4 Numerical Modeling of Shelved Retaining Wall

Various researches have been pursued in terms of shelved retaining wall as mentioned in the above literature. From the literature, it has been inferred that the Mohr–Coulomb model in a FEM tool allows for the lateral earth pressure distribution but is seen to increase considerably due to the loading–unloading in staged construction. Therefore, an advanced soil model is preferred in this study. A 14 m high retaining wall with cohesionless backfill has been chosen for the study. A finite element numerical package (PLAXIS 3D) has been used to understand the pressure distribution on the stem and the relief shelves. The sectional dimensions are as shown in Fig. 3. The basic model consists of a 14 m high stem resting on a base slab of length 7 m and a thickness of 1 m. Six models, namely R_0, R_2, R_4, R_7, R_10, R_3n and R_4n, have been constituted in this paper and the details are as shown in Fig. 4. 'R_0' is for a simple cantilever retaining wall, series 'R_2, R_4, R_7 and R_10' are for single shelved walls and series 'R_3n and R_4n' are for multi-shelved walls. Literature has already established that as the thickness of the shelves increase, there is a reduction in lateral earth pressure. Therefore, a study on thickness of the shelves is not incorporated in this study. A constant shelf thickness of 0.5 m is maintained in all models.

The meshing of the model is divided into 26,367 10-noded tetrahedral elements with local refinement around the stem of the retaining wall for better results. This results in the element size ranging from 0.2137 to 2.554 m. The dimensions are designed taking into consideration that the model should be a plain strain problem and the boundary does not affect the results obtained. Default boundary conditions as defined in PLAXIS 3D have been found sufficient for the model. Sample mesh models for a cantilever retaining wall and a shelved retaining wall are as shown in Fig. 5. The retaining wall is designed using linear elastic model (LE). The backfill soil and the soil below retailing wall are assumed to be the same and are modeled using Hardening Soil model (HS). The properties defined are as given in Table 1.

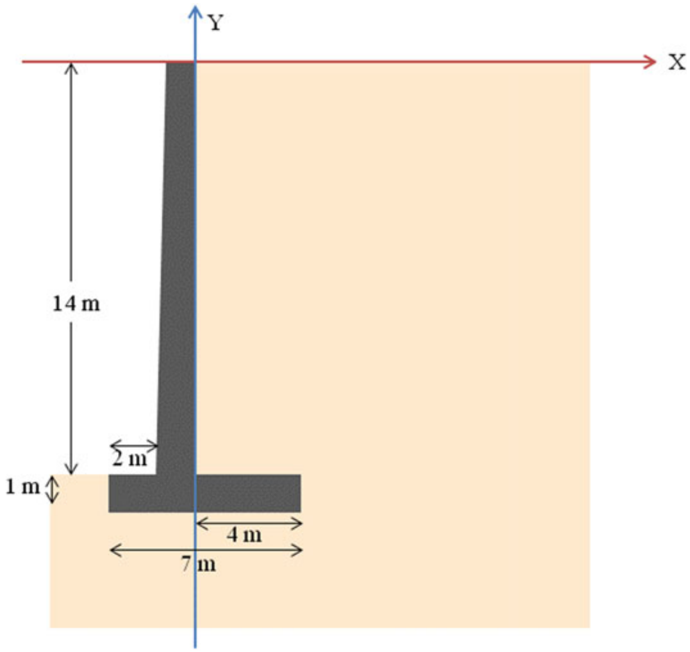

Fig. 3 Geometry of retaining wall

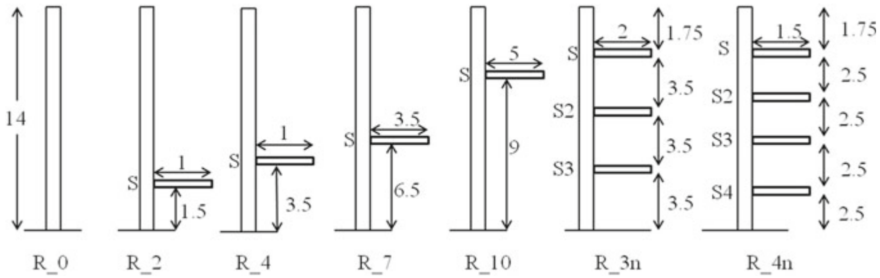

Fig. 4 Geometrical variation of various models

5 Cantilever Retaining Wall

The general assumption of theoretical design for a cantilever retaining wall is that the soil wedge gets fully mobilized and reaches the active earth pressure. However, in reality, the active pressure in the soil lies somewhere between that of an active pressure zone and that of at rest condition. To determine the effect of shelves, we need to first understand the actual mobilization. Figure 6 indicates the actual coefficient of earth pressure mobilized from a FEM model for a simple cantilever retaining wall for a particular soil and height of backfill. The stem top deflection is quite high when

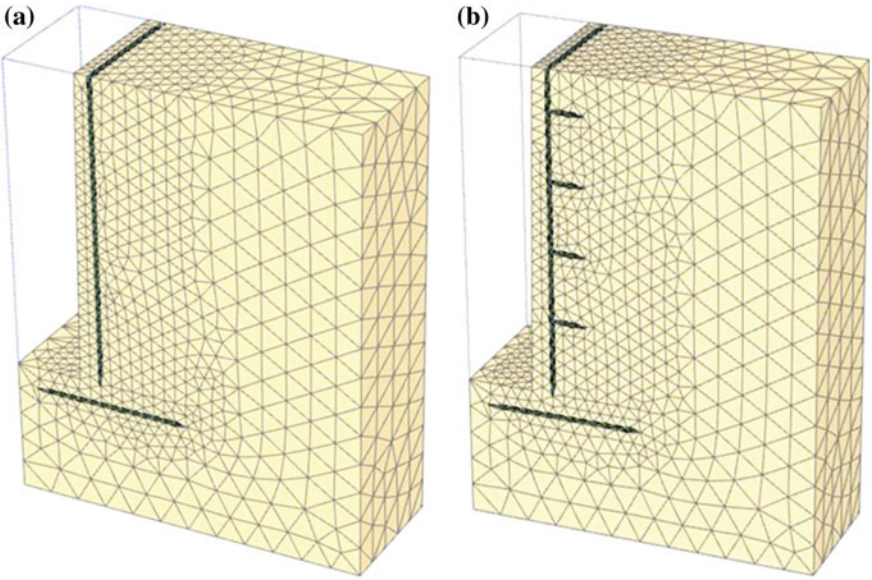

Fig. 5 Meshing of retaining wall model in PLAXIS 3D **a** without shelves and **b** with shelves

Table 1 Material properties used in the model

Parameters	Unit	Retaining wall	Backfill
Material model	–	Linear elastic	Hardening soil
Unit weight, γ	kN/m^3	25	17
Young's modulus, E	kPa	31,622	–
Poisson's ratio, ν	–	0.15	–
E_{50}^{ref}	kPa	–	10,000
E_{oed}^{ref}	kPa	–	10,000
E_{ur}^{ref}	kPa	–	30,000
Power, m	–	–	0.5
Cohesion, C	kPa	–	5
Friction angle, φ	°	–	38
Dilatancy angle	°	–	4

compared to the deflection at the base. This displacement mobilizes the soil wedge and the pressure moves from at rest to that of active pressure at the top. At the base of the retaining wall, no displacement is felt. Therefore, the condition remains in at rest position. It can be seen that the pressure remains close to that of active earth pressure in the case of the stem top while, at the bottom of the stem, the pressure

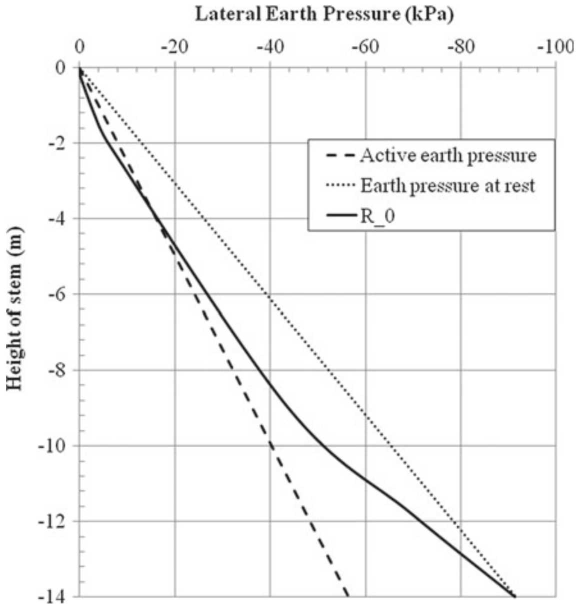

Fig. 6 Comparison of lateral earth pressure in cantilever model with active pressure and pressure at rest

indicates that it is quite close to that of the retaining wall at rest condition. Klein [15] proposed the theoretical model with coefficient of active earth pressure (K_a). However, in this paper, the coefficient of earth pressure at rest (K_0) has been adopted due to this reason.

6 Effect of Shelf Position

From literature, it is understood that introduction of shelves in the stem of the cantilever retaining wall reduces the lateral earth pressure acting on to the stem. The shelf on itself is subjected to normal stresses from the soil weight in the backfill it retains. This normal stress is transferred to the stem as a moment on to the stem. The length and placement of shelf play a crucial role in both the normal stress on the shelf and the lateral earth pressure on the stem. In Fig. 7a, the shelf is placed at a height of 1.5 m as shown in Fig. 4 with the length of shelf as 1 m for it to intersect the rupture plane based on Eq. (2). The earth pressure obtained from the FE simulation of 'R_2' is compared with the theoretical values obtained from Klein [15] and the FE model of a cantilevered retaining wall. Similar comparisons have been made for R_4, R_7 and R_10.

As seen from Fig. 7, the positioning of the shelf plays a major role in the reduction of the lateral earth pressure on the wall. In the case of R_2, where the shelf is present 1.5 m from the base of the retaining wall, the pressure at the top of the stem is reduced when compared to that of a cantilevered retaining wall while there is an

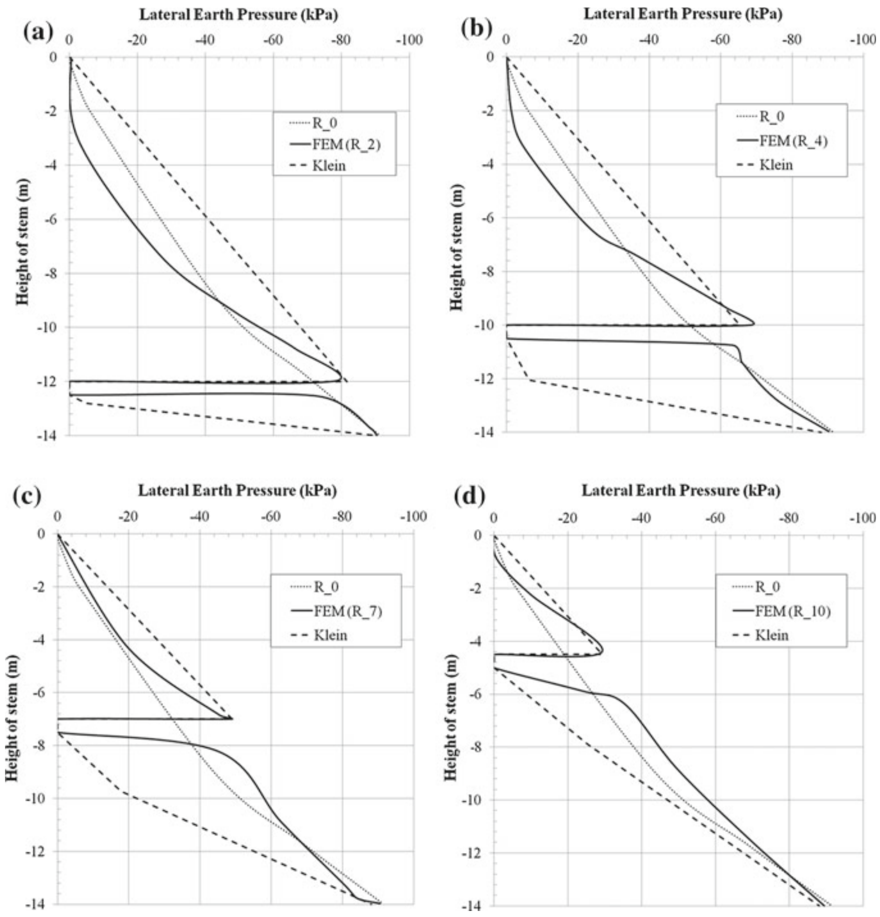

Fig. 7 Comparison of lateral earth pressure for cantilever retaining wall and single shelved retaining wall at various positions. **a** Model R_2, **b** model R_4, **c** model R_7 and **d** model R_10

increase in the stress just on top of the stem. This increase is due to the resistance of the shelf for soil movement, leading to a slight increase in the lateral earth pressure. For overturning moment computation, the lever-arm for the zone where increase in pressure is observed, is quite low. However, for the reduction of stress at top, the lever-arm is quite high. The effective moment due to the product of pressure and lever-arm results in reduction of the overturning moment.

From Fig. 10, it can be seen that the lateral force on the stem in the cases of R_2 and R_4 is reduced by 40% and 37%, respectively, while the reduction in R_7 and R_10 yields a reduction of 28 and 25%. This reduction might be misleading as the moment computed in the cases of R_2 and R_4 has a moment reduction of 24 and 19% while there is an increase in moment by 6% in the case of R_7 and 5% increase in the case of R_10. Another observation is that even though the shelf at

Table 2 Moment in kNm due to normal stress on the shelves

Sl. no.	Model	Moment due to pressure acting normal to the shelves (kNm)			
		Shelf S	Shelf S2	Shelf S3	Shelf S4
1	R_2	31.92	–	–	–
2	R_4	223.91	–	–	–
3	R_7	840.09	–	–	–
4	R_10	1366.62	–	–	–
5	R_3n	41.26	117.95	206.19	–
6	R_4n	17.76	41.44	69.56	98.97

R_2 has around 12 m of backfill as surcharge, the end moment created due to this surcharge acting normal to the shelf is 31 kNm. This is because the length of the shelf is shorter when compared to all the other models. The moment developed due to pressure acting on shelf/shelves on all models is given in Table 2. It can be seen that the moment increases considerably due to the change in length even though the normal stress decreases as the shelf placement is moved toward the top of the stem.

It is observed that there is a slight increase in the lateral earth pressure just above the shelves. This is due to introduction of 'stiffer' shelf which offers rigidity, which in turn increases the stress locally at that location. This is in concurrence with the inference by Shehata [13]. The theoretical observations, such as in the case of Klein [15], do not take the stiffness change into consideration and observe a linear pattern. It is also observed that the lateral earth pressure at the base remains constant irrespective of the height of provision of shelves and the length of the shelves. This is in concurrence with the theoretical solution proposed by Klein [15]. It can also be observed that the provision of a single shelf is effective in the cases of R_2 and R_4 which is below one-third of the height of stem when compared to R_7 and R_10 for stability of the retaining wall. This is in concurrence with the conclusion by Shehata [13] that for a single shelved system, the shelf should be placed from one-third from the base of the stem for effective reduction in lateral earth pressure.

7 Effect Due to Number of Shelves

Considering the effectiveness of a single shelved retaining wall placed at one-third from the base, a wall with multiple shelves is being considered. Equally spaced, equally long, short shelves are placed and designed to intersect the rupture plane. Two models, namely R_3n and R_4n, are utilized in this study. 'R_3n' consists of three shelves spaced at 3.5 m intervals from the base of the slab. For the shelves to intersect the rupture plane, created by the shelf below, a length of 2 m is adopted for the shelves based on Eq. (2). Similarly, 'R_4n' consists of four numbers of shelves with lengths of 1.5 m and spaced 2.5 m apart. It is to be noted that the cumulative length of the shelves in both the models remains the same.

It can be observed from Fig. 8 that the pressure at shelf levels predicted by Klein [15] and that from FE model is a little high when compared to that of the cantilever retaining wall. Similarly, in Fig. 9, the cantilever retaining wall's pressure value is quite less in comparison with the other models at the position of shelves. Comparing

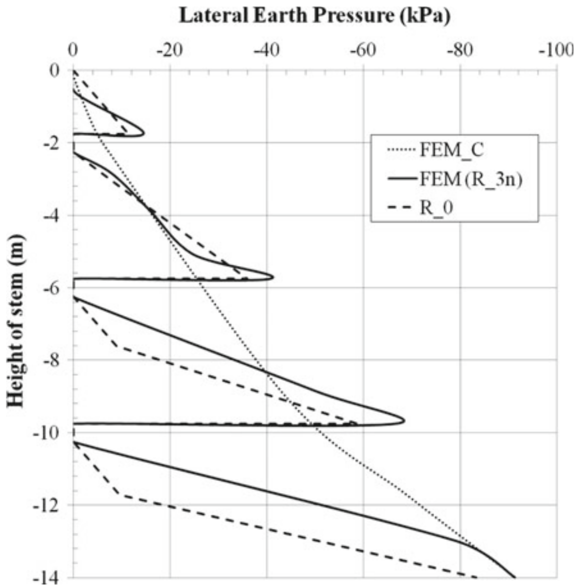

Fig. 8 Lateral earth pressure for three shelved retaining pressure

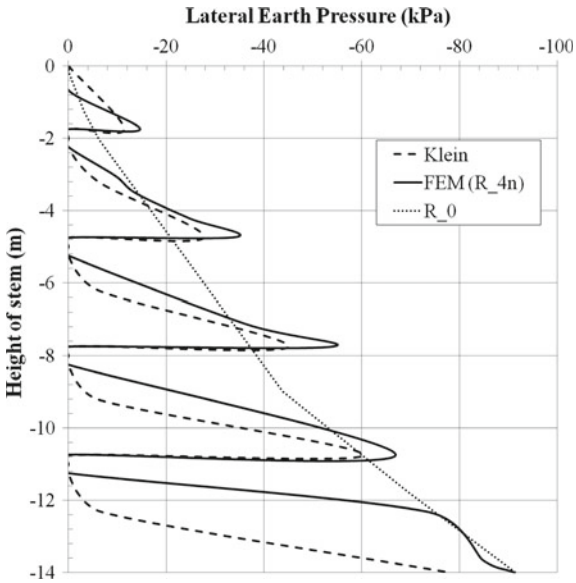

Fig. 9 Lateral earth pressure for four shelved retaining pressure

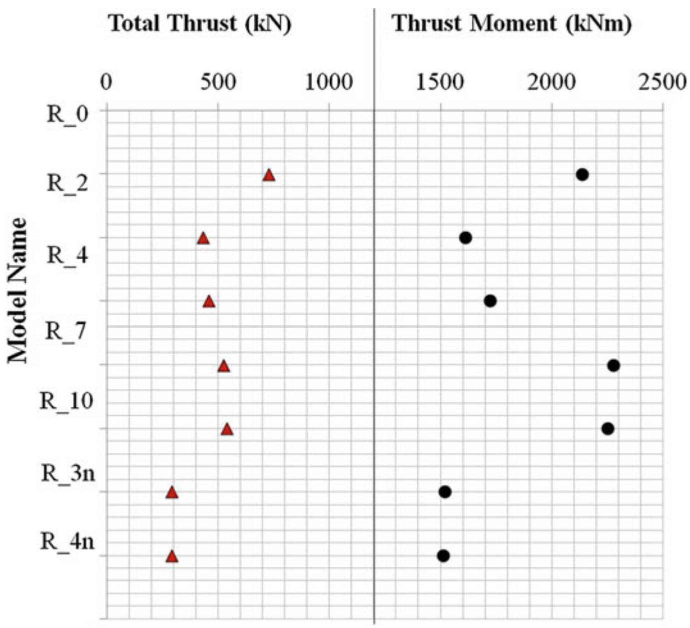

Fig. 10 Comparison of force and moment on the stem for various FEM models

both Figs. 8 and 9, we can see a little decrease in pressure by the introduction of an additional shelf, resulting in little reduction of pressure acting on the stem. However, when compared to that of a cantilever retaining wall, a decrease in 59.81% in the thrust for R_3n while a decrease of 59.9% is felt in the case of R_4n. Similarly, the moment capacity is seen to reduce to about 28% while that of R_4n is 29%. It is seen that introduction of additional shelves need not proportionally mean a decrease in lateral earth pressure on the stem. From Fig. 10, we can see that the moment and the thrust R_3n and R_4n remain almost constant. However, we also need to consider the normal pressure acting on the stem. From Table 2, we can see that a reduction of about 50% of moment is seen on almost all the shelves by the introduction of an additional shelf. It is to be understood that this moment on the shelves also gets transferred to the stem of the retaining wall, and therefore, the overall stability of the structure needs to be considered.

8 Conclusion

The paper studies the effect of position of the shelf and the length of the shelf on the retaining wall. It additionally studies the effect of using more than one shelf on the retaining wall by using a theoretical method proposed by Klein [15]. It had already been established through literature that provision of shelves to the retaining wall proves beneficial for reducing the lateral earth pressure on the wall. This reduction in lateral earth pressure reduces the overturning moment in terms of stability, thus proving economical, especially in cases where the height of the soil to be retained is quite high. A lot of researchers have worked on this structure, both theoretically and experimentally to determine how efficient provision of shelves is to the structure. However, all the efforts have been toward a single shelved retaining wall or two shelved retaining wall. In some literature like the case study of retaining wall failure in Hyderabad, multi-shelved retaining walls were studied. However, the exact efficiency of the multi-shelved retaining walls has not been thoroughly studied. Under the assumption that the shelf rests on a fully compacted soil and that the rigid connection between the shelf and stem has been analyzed for fixed end moment, a study has been carried out for various models using a finite element package.

From the study, it is found that the lateral earth pressure on the stem of the retaining wall significantly reduces due to the introduction of shelves. It is also to be understood that provision of multi-shelved retaining wall is much more efficient than that of single or double shelved retaining wall. However, increase in number of shelves does not mean a significant decrease in the lateral earth pressure on the stem. It is also to be understood that provision of three 2 m shelf (R_3n) is much more economical than one 5 m shelf at 10 m (R_10) from the base. However, provision of too many shelves may shift the failure plane further away from the wall, which might create other stability issues. It is also possible that the shelf–stem connection is of importance and needs to be further studied. The structural stability and the stability of the shelves against the normal stress due to backfill soil have to also be studied.

References

1. Chauhan, V. B., Dasaka, S. M., & Gade, V. K. (2016). Investigation of failure of a rigid retaining wall with relief shelves. *Japanese Geotechnical Society Special Publication, 2*(73), 2492–2497. https://doi.org/10.3208/jgssp.TC302-02.
2. Khan, R., Chauhan, V. B., & Dasaka, S. M. (2016). Reduction of lateral earth pressure on retaining wall using relief shelf: A numerical study. In *Proceedings of International Conference on Soil and Environment* (117 pp). Bangalore, India.
3. Chauhan, V. B., & Dasaka, S. M. (2016). Behavior of rigid retaining wall with relief shelves with cohesive backfill. In *Proceeding of 5th International Conference on Forensic Geotechnical Engineering* (pp. 350–357). Bangalore.
4. Bowles, J. E. (1996). *Foundation analysis and design*. McGraw-Hill.
5. Jumikis, A. R. (1964). *Mechanics of soils*. New Jersey: D. Van Nostrand Co., Inc.
6. Yakovlev, P. I. (1964). Experimental investigations of a new type of relieving device for retaining walls. In *Scientific Paper in 'Hydraulic Engineering' (in Russian)*, No. 3. Morskoi Transport.
7. Yakovlev, P. I. (1964). Investigation of the behavior of relieving platforms of retaining walls. In *Scientific Paper in Hydraulic Engineering, Russian*, No. 3. Morskoi Transport.
8. Yakovlev, P. I. (1965). Calculation of relieving beams. In *Scientific Papers 'Sea Ports' (in Russian)*, No. 1.
9. Yakovlev, P. I. (1966). Application of S. S. Golushkevich's method to calculation of retaining walls with relieving platforms. *Izvestiya VUZOV. Stroitel's tovo Arkhitektura* (9).

10. Yakovlev, P. I. (1974). *Experimental investigations of earth pressure on walls with two platforms in the case of breaking loads relieving on the backfill*. Translated from Osnovaniya, Fundamenty Mekhanika Gruntov, No. 3 (pp. 7–9). Odessa Institute of Naval Engineers.
11. Raychaudhuri, P. R. (1973). Design of retaining walls with relieving shelves. *Journal of the Indian Roads Congress, 35*(2), 289–325.
12. Phatak, D. R., & Patil, V. (1975). Effect of relief shelves on earth pressure. *Institute of Engineers (India) JournalC1, 55*, 156–159.
13. Shehata, H. F. (2016). Retaining walls with relief shelves. *Innovative Infrastructure Solutions, 1*(1), 4. https://doi.org/10.1007/s41062-016-0007-x.
14. Padhye, R. D., & Ullagaddi, P. B. (2011). Analysis of retaining wall with pressure relief shelf by Coulomb's method. In *Proceedings of Indian Geotechnical Conference* (pp. 671–673).
15. Klein, G. K. (1964). *Calculation of retaining walls*. Moscow: Vysshaya Shkola. (in Russian).