Investigation of failure of a rigid retaining wall with relief shelves

Vinay B. Chauhan, Satyanarayana M. Dasaka, and Vinil K. Gade

ABSTRACT

Present study attempts to investigate the possible reasons behind the failure of a cantilever retaining wall with relief shelves, which is located in the heart of Hyderabad city, India. A pressure relief shelf is a finite width, thin horizontal cantilever platform extending into the backfill, which are constructed monolithically with the stem of the retaining wall. Number of such shelves is constructed at regular spacing along the height of the wall. From the limited theoretical studies, it is noted that the provision of relief shelves, extending beyond the rupture surface in the backfill, can considerably reduce the earth pressures on the retaining wall and subsequently increase the stability of the retaining structure. The height of the failed retaining wall ranges from 10 to 13.9 m and retains a loose to medium dense sandy soil backfill, and constructed with 5 relief shelves. After few years of construction, a portion of retaining wall of about 20 m length had collapsed and adjoining 2 m length had severely distressed, immediately after the end of a monsoon. The preliminary post-failure investigation revealed that quality of concrete used in construction was satisfactory, and the construction joints were intact. Cracks due to failure had propagated almost up to the full thickness of reinforced concrete wall. To get more insight about the causes of failure, numerical analysis of retaining wall with pressure relief shelves is carried out using widely used geotechnical numerical code, FLAC. From the preliminary analysis, it is noted that, though the lateral thrust on the retaining wall in the presence of relief shelves is reduced by 43-48%, use of inappropriate magnitude and distribution of lateral earth pressure in the design calculations might have attributed to the failure of the wall.

Keywords: retaining wall, relief shelf, earth pressure, numerical modelling, FLAC

1 INTRODUCTION

Retaining walls are an integral part of almost all infrastructure projects, to support vertical or near vertical backfills. Lateral earth pressure on the retaining walls is the key factor influencing the sectional dimensions of the wall. So, by reducing lateral earth pressure, sectional dimensions of retaining wall as well as cost of project can be substantially reduced. There are many methods available to reduce the lateral earth pressure like use of geo-inclusion, light weight backfill, to name a few. Provision of relief shelves connected to the stem of cantilever wall, can reduce the earth pressure. Relief shelves are horizontal platforms, which are constructed monolithically with the stem of wall, and extend into the backfill at right angles, throughout the length of the retaining wall. Number of such shelves is constructed at regular spacing along the height of the wall. Retaining wall with relief shelves is a least explored technique. A few researchers previously proposed this technique without any systematic analysis and proper validation. This area has never well understood to explain the mechanism behind lateral earth pressure reduction (Jumikis 1964; Chaudhuri et al. 1973 and Bowles 1977), because of its particularity, complexity and existing variable factors, the mechanical behaviour of this structure is unclear (Liu et al. 2013). Such walls were constructed in past but unfortunately their behaviour was never well documented. Hence, the present study is aimed at understanding the behaviour of such walls and to explore the effectiveness of these walls to reduce lateral earth pressure and lateral thrust on the wall and to get proper insight about the associated mechanisms involved in the pressure reduction.

2 LITERATURE REVIEW

Jumikis (1964) studied the effect of provision of relief shelves on the earth pressure and noted that extending them beyond the rupture surface in the backfill can considerably reduce the lateral earth pressure and increase the stability of retaining wall. Chaudhuri et al. (1973) analysed the effect of single relief shelf on the total thrust on the cantilever retaining wall. The total thrust due to provision of a shelf was calculated from the stability analysis of wedges. Coulomb’s theory was used to calculate the thrust on
the wall, and weight of soil above the relief shelf was excluded while taking weight of failure wedge. With the help of model retaining walls constructed in the laboratory, it was showed that the maximum height of sand that could be retained by wall just prior to the incipient overturning is higher in case of walls with relief shelf than walls without relief shelf. Bowles (1997) suggested such walls as a possible solution for high retaining walls, while cautioning that the soil must be well compacted up to relief shelf. Consolidation of backfill beneath the shelves may make the shelves act as cantilever beams, and cause the bending of the shelves (Fig. 1).

![Cantilever retaining wall with relief shelves](image1)

When this occurs, either the shelf breaks off or the wall above tends to move into backfill and subjected to higher passive pressures. The wall must be of sufficient thickness and well reinforced on both compression and tension faces to carry this anticipated shear and bending moment. With the help of bending moment and shear force diagrams of the stem and modified earth pressure diagram, Kurian (2007) showed the contribution of the relief shelf to the overall stability of the retaining wall. It was cautioned that the soil below the relief shelf should not provide any support to relief shelf. Liu et al. (2011) conducted model tests on sheet pile wall with single relief shelf to get the lateral earth pressure distribution on upper wall by varying the ratio of height of stem and the width of relief shelf under embankment and external load. From the model test, it was concluded 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. (2013) 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 wall with relief shelves in Hyderabad, India](image2)

A well documented case of failure of retaining wall with relief shelves has been reported in Hyderabad, India, where retaining walls of varying height of 10 to 13.9 m with multiple relief shelves were constructed to retain the soil. The above structure had failed after few years of construction. Cracks on the stem of retaining wall just below one of the relief shelves were noted, as shown in Fig. 2. Reasons behind the failure of structure are unknown yet. Most likely the lateral earth pressure was not estimated properly. Retaining walls with relief shelves are increasingly being used at several places in southern India, but unfortunately design guidelines in terms of number, position and width of relief shelves are not developed yet. Failure of such structures at few places has motivated the authors to investigate the reason behind the failure of retaining walls with relief shelves at Hyderabad, India, as well as to understand the mechanism and efficiency of retaining walls with relief shelves.

### 3 INVESTIGATION OF FAILURE OF A RIGID RETAINING WALL WITH RELIEF SHELVES

Failed retaining wall at Hyderabad, India, with relief shelves has been analysed in FLAC. Sectional dimensions of the wall (Fig. 3b) were obtained from a forensic report (unpublished). As the backfill and foundation soil properties were not available to the authors, acceptable range of material properties were taken from Athanasopoulos-Zekkos et al. (2012), as shown in Table 1.
From the numerical analysis, it is found that retaining wall has failed and earth pressure distribution cannot be captured due to failure. It is found that due to use of high width of relief shelves, the passive pressure below the relief shelves has significantly increased, which has created the unanticipated high tensile and compressive stresses on the faces of stem of wall just below one of the relief shelves, as shown in Fig. 3(a). Contrary to conventional rigid retaining cantilever walls, compressive stresses (7.01 MPa) were recorded on the face of stem towards the backfill and tensile stresses (7.15 MPa) on the opposite face. These unanticipated stresses might have been ignored during the design of the retaining wall, which resulted cracking of the stem of retaining wall.

4 MODELLING OF RETAINING WALL WITH RELIEF SHELVES

To provide a possible solution for the failed retaining wall with relief shelves, a cantilever retaining wall having a height of 14.2 m has been chosen for the present study (Fig. 4). Five cantilever relief shelves of same widths are provided at different heights of the wall. The thickness of relief shelf is kept as 0.3 m.

Dry cohesionless soil has been selected as backfill and foundation soil (same as shown in Table 1). Factor of safety of retaining wall in sliding and overturning are estimated as 1.55 and 2.40, respectively. Width of relief shelf is varied from 0.6 m to 1.5 m to examine the reduction of lateral earth pressure and total thrust. Length of wall is considered as 1.0 m for analysis. Conventional retaining wall without relief shelves (Fig. 4a) is hereafter referred to as RS 0.0. Retaining wall with relief shelves is shown in Fig. 4b, where B represents width of relief shelf which is varied as 0.6, 0.9, 1.2 and 1.5 m, having thickness of 0.3 m and referred to as RS 0.6, RS 0.9, RS 1.2 and RS 1.5. Fig. 5 shows the numerical grid considered to simulate the rigid retaining wall. Pinned boundary condition at bottom of foundation and roller boundary condition at vertical end of soils are chosen to represent field conditions. The rigid wall is modelled as elastic material. Backfill material is modelled as a purely frictional, elasto-plastic material following Mohr-Coulomb failure criterion. Material properties considered in the analysis are shown in Table 1. The interface between wall and soil is modelled as linear spring-slider system with interface shear strength defined by the Mohr-Coulomb failure criterion. The normal stiffness \( k_n \) and shear stiffness \( k_s \) of the interface are taken as follows (Itasca 2011):

\[
k_n = k_s = 10 \times \max \left[ K + \frac{4}{3} G \right] (\Delta z)_{\min}
\]  

where \((\Delta z)_{\min}\), \(K\) and \(G\) are the smallest dimension in normal direction, bulk modulus and shear modulus of the continuum zone adjacent to the interface, respectively.
5.1 Contact pressure below base slab
For a rigid cantilever retaining wall, contact pressure below base slab is governed by weight of wall, centre of gravity of wall, and lateral thrust of soil. Variation of contact pressure below base slab for all retaining walls considered in the present study is shown in Fig. 7. Contact pressure is marginally lower in case of walls with shelves. With increase in width of relief shelf, contact pressure below the base slab has reduced ranging from 4.4-7.2% only.

5.2 Lateral earth pressure on the retaining wall
Earth pressure distribution of all walls with and without relief shelves have been studied and shown in Fig. 8 and Fig. 9. Provision of five relief shelves has made the whole retaining wall into six small segments. From Fig. 8 and Fig. 9, it can be observed that lateral earth pressure in top two segments increases with the increase in width of relief shelf (RS 0.6, RS 0.9 and RS 1.2, RS 1.5) and in bottom two segments lateral earth pressure decreases (RS 0.6, RS 0.9 and RS 1.2, RS 1.5) with the increase in the width of relief shelf.

5 RESULTS AND DISCUSSION
In the present analysis, rigid retaining walls with five relief shelves provided at different heights of wall having equal widths are analysed with FLAC3D. The lateral earth pressure distribution, contact pressure below base slab, total lateral thrust, backfill settlement and deflection of relief shelves are analysed and discussed below.
Contrary to results of Liu et al. (2013), passive pressure just below the relief shelves has found in all cases of retaining wall with relief shelves. It is also found that with increase of width of relief shelves total passive thrust increases.

5.3 Total thrust
Total thrust is calculated as the area of lateral earth pressure diagrams and results are shown in Table 2.

Table 2. Total thrust and reduction in thrust on retaining walls

| Wall type | RS 0.0 | RS 0.6 | RS 0.9 | RS 1.2 | RS 1.5 |
|-----------|--------|--------|--------|--------|--------|
| Total thrust kN/m | 496.2  | 280.2  | 275.2  | 273.6  | 258.5  |
| % Reduction in thrust | 43.5   | 44.5   | 44.9   | 47.9   |

A noteworthy amount of total thrust reduction is obtained by provision of relief shelves. A range of 43.5-47.9% of total thrust reduction is achieved by provision of relief shelves.

5.4 Surface settlement profile of backfill
Surface settlement of backfill is a criterion of serviceability of retaining walls. Excessive backfill settlement leads to collapse of backfill soil and subsequently failure of surrounding structures. Fig. 10 represents the surface settlement of all retaining walls considered in this study. Backfill settlement near the wall is decreasing with the increase in width of relief shelf. These relief shelves are working like a horizontal obstruction for the backfill vertical settlement near the stem of retaining wall. Backfill settlement near the wall is ranging between 6-10 mm and it gradually increases up to a maximum value of 16 mm for RS 0.6, RS 0.9, RS 1.2 and RS 1.5 up to 2 m away from wall and further it attains a constant value of 15 mm. With increase in width of relief shelf, backfill settlement has been reduced significantly by 10 mm near the wall stem compared to retaining wall without relief shelves.

5.5 Lateral Displacement of retaining wall
Lateral displacement of wall away from backfill has been shown in Fig. 11. It can be seen that provision of relief shelves to the wall has reduced the lateral displacement of the wall from 9.58 mm (wall without relief shelf) to 3.44-2.43 mm (walls with relief shelf).

5.6 Deflection of relief shelves
Maximum deflection of all relief shelves from top to bottom are compared in Fig. 12, and summarized in Table 3. The notations S1, S2, S3, S4 and S5 represent...
the relief shelves from top to bottom of retaining wall. Deflection of relief shelves from top to bottom of wall has increased and found maximum for bottommost relief shelf for all retaining walls with relief shelves. Deflection of relief shelves has significantly increased where the width of relief shelf is greater than 1.2 m.

Fig. 12. Maximum vertical deflection profile of relief shelves

Table 3. Maximum deflection (mm) of relief shelves for various retaining walls

| Relief Shelf | RS 0.6 | RS 0.9 | RS 1.2 | RS 1.5 |
|--------------|--------|--------|--------|--------|
| S1           | 1.72   | 2.17   | 2.45   | 5.54   |
| S2           | 2.24   | 2.38   | 2.59   | 6.35   |
| S3           | 2.71   | 2.8    | 2.96   | 6.4    |
| S4           | 2.82   | 3.08   | 3.32   | 6.62   |
| S5           | 2.91   | 3.23   | 3.47   | 6.65   |

This observation would restrict maximum width of relief shelves to 1.2 m. Higher widths of relief shelves lead to excessive deflection due to its own weight, which may further increase due to creep. Among all the cases of retaining wall with relief shelves, RS 0.6 provides maximum benefit, without leading to excessive deflection of relief shelves.

Verification of the above results through use of physical models is underway, which may enhance the efficacy of the retaining walls with relief shelves.

6 CONCLUSIONS

The study involves comprehensive finite difference numerical analysis to examine the possible reason of failure of retaining wall with relief shelves. It is found that use of higher width of relief shelves has significantly increased the passive pressure below the relief shelves, which has created the unanticipated high tensile and compressive stress on the faces of stem of wall just below one of the relief shelves. This unanticipated stresses might have been neglected in the designs, resulting in failure/distress of retaining wall. From the present study, it is noted that this technique of reducing earth pressure on retaining walls may prove economical. Among all the cases of retaining wall with relief shelves, RS 0.6 proves viable, without leading to excessive deflection of relief shelves. The following conclusions are drawn from the present study.

1. Retaining walls with relief shelves can considerably reduce the total thrust on wall in the range of 43–48%.
2. Among all walls considered in the present study, using relief shelves of width 0.6 m will be effective without leading to excessive deflection of relief shelves.
3. Backfill surface settlement decreases with provision of relief shelves.
4. Deflection of relief shelf is proportional to the width of relief shelf, and it also increases from top shelf to bottom shelf a given retaining wall with relief shelves.
5. Passive pressure is getting introduced just below the relief shelves. More the width of relief shelf higher the passive pressure on the retaining wall.
6. Contact pressure below the base of retaining wall is also reduced with the provision of relief shelves.

REFERENCES

1) Athanasopoulos - Zekkos, A., Lamote, K., Athanasopoulos, G.A. (2012): Use of EPS geofoam compressible inclusions for reducing the earthquake effects on yielding earth retaining structures, Soil Dynamics and Earthquake Engineering, 41, 59-71.
2) Bowles, J.E. (1997): Foundation analysis and design, 5th Edition, McGraw-Hill, Singapore.
3) Chaudhuri, P.R., Garg, A.K., Rao, M.V.B., Sharma, R.N., Satija, P.D. (1973): Design of retaining wall with relieving shelves, IRC J. 35(2), 289 - 325.
4) Ertesvåg, O. L., and Trandafir, A.C. (2011): Reduction of lateral earth forces acting on rigid non-yielding retaining walls by EPS geofoam inclusions, J. Mater. Civil Eng., 23(12), 1711-1718.
5) FLAC 3D (5.0), Itasca, 2011.
6) Jumikis, A.R. (1964): Mechanics of soils, D. Van Nostrand Company Inc, Princeton NJ.
7) Kurian, N.P. (2007): Design of foundation systems, principles and practice, 3rd Edition, Narosa Publishing House, Delhi.
8) Liu, G., Hu, R., Pan, X., Liu Y. (2011): Model tests on earth pressure of upper part wall of sheet pile wall with relieving platform (In Chinese), Rock and Soil Mechanics, 32(2), 103-110.
9) Liu, G., Hu, R., Pan, X., Liu Y. (2013): Model tests on mechanical behaviors of sheet pile wall with relieving platform. (In Chinese), Chinese J. Geotech. Eng., 35(1), 94-99.
10) Nadim, F. and Whitman, R.V. (1983): Seismically induced movement of retaining walls, J. Geotech. Eng., 10.1061/(ASCE)0733-9410(1983)109:7(915).