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Forensic investigation of a rigid retaining wall with relief shelves using static force analysis

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ABSTRACT

The present study attempts to investigate the possible reasons behind the failure of a cantilever retaining wall with relief shelves which is located in the populated area of Hyderabad city, India. This study is carried out using an analytical model based on static force analysis for a retaining with relief shelves to provide the most possible reason behind the failure of the aforementioned retaining wall and to provide suggestion for the optimum width of relief shelves for this particular retaining wall.

Keywords: retaining wall; relief shelf; earth pressure; earth pressure reduction; forensic investigation

1 INTRODUCTION

Retaining walls with relief shelves have been gaining popularity in many countries for a sustainable and cost-effective solution of retaining wall requirements (Chauhan et al. 2016). This specific retaining wall consist a thin horizontal cantilever platform having a finite width, named as relief shelf, extending into the backfill, which is constructed monolithically with the stem of the retaining wall. The number of such shelves is constructed at regular spacing along with the height of the wall (Chauhan and Dasaka 2016). From the previous studies, it is noted that the provision of relief shelves can considerably reduce the earth pressures on the retaining wall and subsequently increase the stability of the retaining structure (Chauhan et al. 2019). However, in recent past, it is noted that a cantilever retaining wall with relief shelves which is located in the populated area of Hyderabad city, India got failed. The height of the failed retaining wall ranges from 10 to 13.9 m and constructed with 5 relief shelves. This wall retains a loose to medium dense sandy soil backfill and after few years of construction, a portion of retaining wall of about 20 m length had collapsed and adjoining 20 m length had severely distressed. The forensic studies revealed that the quality of concrete used in the wall construction was very satisfactory, and construction defects were completely ruled out. Cracks due to failure had propagated almost up to the full thickness of the reinforced concrete wall (Chauhan et al. 2016).

Moreover, Chauhan et al. (2016) also conducted a numerical analysis using limit equilibrium method for this failed retaining wall with relief shelves and concluded that use of wider relief shelves than the optimum width of relief shelf at various depth of wall were used due to which wall had a tendency to move towards backfill side and induced a stress reversal phenomenon on the faces of wall stem (shown in Fig. 1). Chauhan et al. (2016) reported that compressive

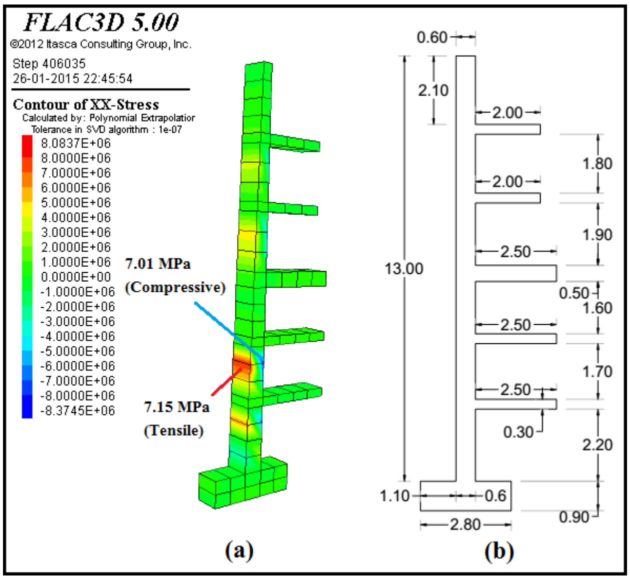

Fig.1. Cantilever retaining wall with relief shelves, Hyderabad (a) result of numerical analysis (b) sectional dimensions (Chauhan et al. 2016)

stresses were recorded on the face of stem towards the backfill and tensile stresses on the opposite face due to higher width of relief shelves. Furthermore, Chauhan et al. (2016) proposed the appropriate width of relief shelves for the failed retaining wall. The outcome of this analysis was based on the selection of width of relief shelves which are sufficient to provide the significant reduction on the total thrust on the wall as well as satisfactory confirming the serviceability criterion for the backfill surface settlement and deflection of relief shelves. With the advancement of research in this area, Chauhan and Dasaka (2018) established the relationships for the maximum allowable widths of relief shelves for achieving maximum reduction of earth pressure behind the wall. Moreover, the recommendation for the arrangement of shelves for the retaining wall are provided based on the static force analysis where an expression in terms of a ratio of intermediate stem height (*h*, cental distance between the two successive relief shelf) to the width of relief shelves (*b*) for the retaining wall with relief shelves is analyzed by considering the static equilibrium of all the forces acting on it. In the present study, the aforementioned work by authors is extended to find out the most possible reason behind the failure of retaining wall with relief shelves.

2 STATIC FORCE ANALYSIS FOR WALL WITH FIVE RELIEF SHELVES

To execute the analysis for the failed retaining wall

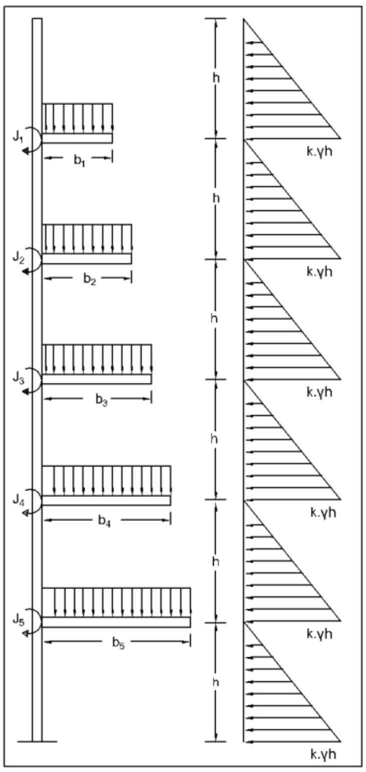

Fig. 2. Stress diagram of retaining wall with five relief shelves

with relief shelves backfilled with soil having density γ with a combination of varying widths of relief shelves (b_1, b_2, b_3, b_4, and b_5) at different levels of wall height, the method proposed by Chauhan and Dasaka (2018) is further extended for wall having five relief shelves as shown in Fig. 2. In this analysis, free body diagrams are drawn at each junction of relief shelf and wall stem (J_1, J_2, J_3, J_4 and J_5) and analyzed further to get the internal reaction in each section of the wall while considering static equilibrium at every junction. Free body diagram of the portion above the junction J_1 is shown in Fig. 3(a), where R_1 and R_2 are the reactions, k is the coefficient of lateral earth pressure and M is the moment at the junction. For equilibrium condition, $\sum M = 0$ at junction J_1, which forms the following equation at J_1.

$$M + \left(b_1^2 \gamma h/2\right) - \left(k\gamma h^2/2\right) \times h/3 = 0 \tag{1}$$

From Eq. (1), it is noted that moment generated due to soil weight carried by shelf is $b_1^2 \gamma h/2$ which is a linear function of the width of relief shelf, b_1.

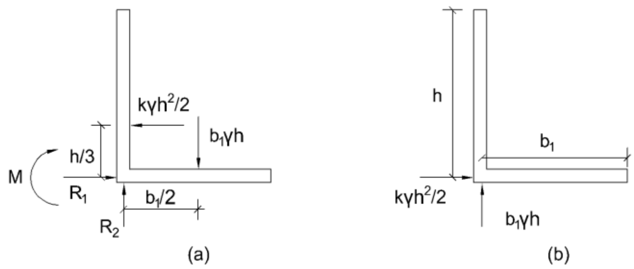

Fig. 3. (a) Free body diagram above the junction J_1;
(b) equivalent free body diagram above the junction J_1

If this moment increases, retaining wall is pushed into the backfill, leading to a possible generation of lateral pressure more than at-rest condition. If, $\sum M = 0$ at junction J_1, maximum allowable width of first relief shelf from the top of the wall stem can be obtained as follows.

$$b_1^2 = kh^2/3 \tag{2}$$

If, $b_1^2 = kh^2/3$, $\sum M = 0$ at junction J_1 and equivalent free body diagram is shown in Fig. 3(b), where reactions R_1 and R_2 can be computed as

$$R_1 = k\gamma h^2/2 \tag{3}$$

$$R_2 = b_1 \gamma h \tag{4}$$

Similarly, free body diagram of the portion above the junction J_2 and J_3 are shown in Fig. 4. For equilibrium condition, at junction J_2, static equilibrium can be written as follows.

$$M + b_2^2 \gamma h/2 + \gamma h\left(b_2 - b_1\right)\left(b_1 + \left(\left(b_2 - b_1\right)/2\right)\right) - \left(k\gamma h^2/2\right)\left[h + h/3\right] = 0 \tag{5}$$

If, $M = 0$, Eq. (5) can be written as follows.

$$b_2^2 \gamma h = b_1^2 \gamma h/2 + \left(k\gamma h^2/2\right)\left(h + h/3\right) \tag{6}$$

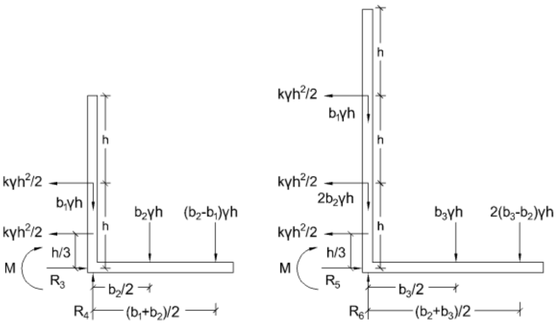

Fig. 4. (a) Free body diagram above the junction J$_2$; (b) free body diagram above the junction J$_3$

It is noteworthy from Eq. (6) that b_1 and b_2 are unknown in the equation, which cannot provide a closed form expression for b_2. However, it can be perceived that b_2 itself is a function of b_1, and the value of b_2 can be evaluated by substituting the value of b_1 in Eq. (6).

So, for a given condition, when the allowable maximum value of b_1 is provided, b_2 can be evaluated by substituting $b_1^2 = kh^2/3$ in Eq. (6), which gives

$$\mathrm{b}_2 = h\sqrt{5k/6} \tag{7}$$

Reactions at junction J$_2$, R_3 and R_4 come out to be

$$R_3 = k\gamma h^2 \tag{8}$$

$$R_4 = 2b_2\gamma h \tag{9}$$

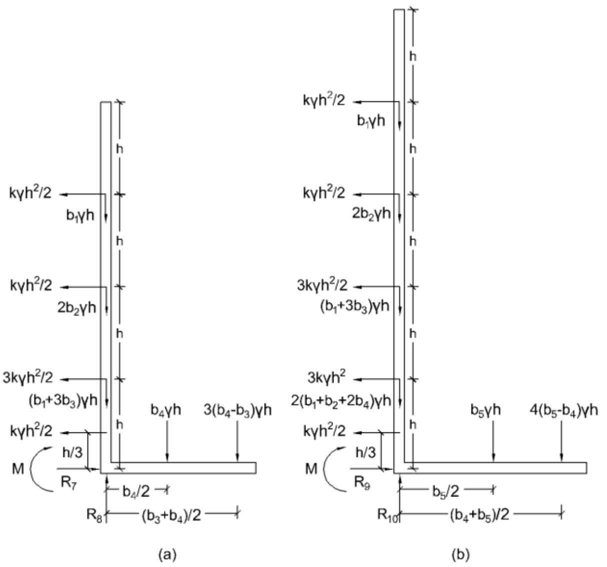

Fig. 5. Free body diagram (a) above the junction J$_4$; (b) above the junction J$_5$

Similarly, for the equilibrium conditions, at junctions J_3, J_4 and J_5 (free body diagram are shown in Figs. 4(b) and 5, static equilibrium equations can be shown as follows in Eqs. (10, 11, and 12) respectively.

$$\begin{aligned} &M + b_3^2\gamma h/2 + 2\gamma h(b_3 - b_2)(b_2 + ((b_3 - b_2)/2)) \\ &- k\gamma h^2/2[2h + h + h/3] = 0 \end{aligned} \tag{10}$$

$$\begin{aligned} &M + b_4^2\gamma h/2 + 3\gamma h(b_4 - b_3)(b_3 + ((b_4 - b_3)/2)) \\ &- k\gamma h^2/2[3h + 3h + 2h + h + h/3] = 0 \end{aligned} \tag{11}$$

$$\begin{aligned} &M + b_5^2\gamma h/2 + 4\gamma h(b_5 - b_4)(b_4 + ((b_5 - b_4)/2)) \\ &- k\gamma h^2/2[4h + 3h + 6h + 6h + h/3] = 0 \end{aligned} \tag{12}$$

For the above Eqs. (10-12), allowable width of relief shelves (b_3, b_4, and b_5) at junctions J_3, J_4, and J_5 can be obtained by substituting $M = 0$ and the maximum allowable values of the relief shelf obtained just above the specified junction in above equations (Eqs. 10-12).

$$b_3 = h\sqrt{5k/3} \tag{13}$$

$$b_4 = h\sqrt{10k/3} \tag{14}$$

$$b_5 = h\sqrt{98k/15} \tag{15}$$

Considering the equilibrium at junctions J_3, J_4, and J_5 in vertical and horizontal directions, reaction forces at junctions J_3, J_4, and J_5 (R_5, R_6, R_7, R_8, R_9, and R_{10}, as shown in Figs. 4 (b) and (5)) can be computed using following equations.

$$R_5 = 3k\gamma h^2/2 \tag{16}$$

$$R_6 = (b_1 + 3b_3)\gamma h \tag{17}$$

$$R_7 = 3k\gamma h^2 \tag{18}$$

$$R_8 = 2\gamma h(b_1 + b_2 + 2b_4) \tag{19}$$

$$R_9 = 6k\gamma h^2 \tag{20}$$

$$R_{10} = \gamma h(4b_1 + 4b_2 + 3b_3 + 4b_4) \tag{21}$$

From the above analysis, it is worth to mention here that for the aforementioned analysis, uniform intermediate stem height was assumed to simplify the complex problem and provide a closed form solution for the maximum allowable width of relief shelf. However, this particular problem can also be solved for non-uniform intermediate stem height but that specific problem cannot be solved for closed form solution. However, the obtained solution would be proposed for given particular values of width of relief shelf and intermediate stem height.

2.1 Calculation for the maximum allowable width of the relief shelf for the failed retaining wall with relief shelf

For the case of failed retaining wall with relief shelves, widths of relief shelves b_1, b_2, b_3, b_4, and b_5 are 2m, 2m, 2.5m, 2.5m and 2.5m, respectively. These relief shelves were provided at intermediate stem height of wall 2.10m, 2.10m, 2.20m, 2.0m and 2.0m from the top to bottom along the height of wall as shown in Fig. 1(b). Lateral active earth pressure coefficient on the wall is taken as 0.27, which is based on the internal friction angle of backfill soil which is 35° (Chauhan et al. 2016). However, the intermediate stem height of wall for the failed retaining wall with relief shelves is not uniform, but to simplify the problem and provide a closed-form solution as per the derivations discussed in the previous section, a uniform intermediate stem height between the two successive relief shelves is assumed to be 2.10m, which is arithmetic average value of all the values (2.10m, 2.10m, 2.20m, 2.0m and 2.0m) of intermediate stem height. As this average value of the intermediate stem height is range of ±4.7%, so this value can be assumed without affecting much the calculation of maximum allowable width of relief shelves at different levels of wall height using Eqs. (2, 7, and 13-15). Based on the intermediate stem height of 2.10m, maximum allowable widths of relief shelf at different height of wall stem are obtained as b_1=0.6m, b_2=1.0m, b_3=1.40m, b_4=2.0m and b_5=2.80m from top to bottom. It is evident that the width of relief shelves provided in the failed retaining wall for first four relief shelves from the top are much higher than the maximum allowable width of relief shelf at corresponding height of wall. Based on above outcome, an appropriate section dimensions for the retaining wall is suggested as shown in the Fig. 6. Moreover, it is also worthy to notice that a very small base width was provided for the failed retaining wall, which has been futher revised based on the (Chauhan et al. 2016) recommendations as shown in the Fig. 6.

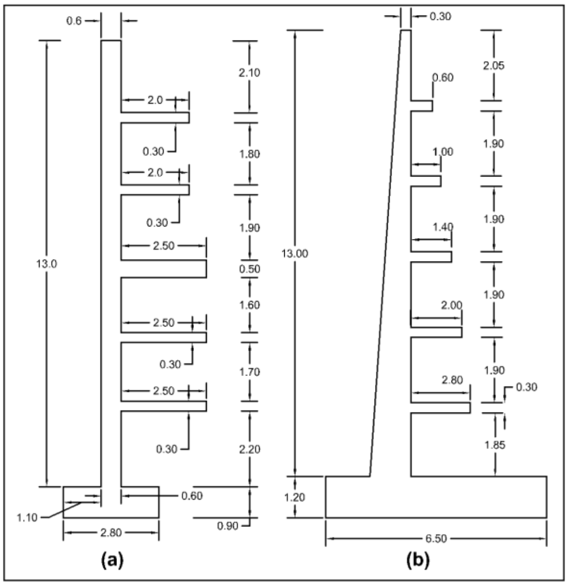

Fig. 6. Comparison of sectional dimensions of (a) failed retaining walls with relief shelves; (b) retaining walls with relief shelves suggested from the present study (all dimensions in m)

Moreover, it has already been established that wider relief shelves have a tendency to move the wall stem towards backfill due to the weight of soil supported by relief shelves (Chauhan et al. 2016). Also, based on the outcome of the present study, the internal reactions at the junction of wall stem and relief shelves, increases significantly due to wider relief shelves. Furthermore, direction of forces on wall might have introduced the stress reversal phomenon on the faces of wall stem as reported by Chauhan et al. 2016. Internal reactions at junctions near the bottom of wall (J_3, J_4, and J_5), increases rapidly, which is majorly attributed due to the wider relief shelves placed above it (Eqs. 17, 19, and 21). This high internal reactions might have intiatiated and propogated the cracks due to in the wall stem, and futher leading to the failure of retaining wall.

3 RESULTS AND DISCUSSION

The present study applies static force analysis to assess the probable reason behind the failure of a rigid retaining wall with relief shelves and proposes that wider relief shelves were provided at four positions out of five positions along the height of wall compared to the maximum allowable width of relief shelves obtained from the analysis discussed in the present study. Authors recommends that for such walls, width of relief shelf should be increases from top to bottom and width of relief shelf must confirm the recommendations laid for maximum allowable width of relief shelf.

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