Effect of Counterforts and Buttresses on Retaining Wall using Finite Element Analysis

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Abstract. Retaining walls are used with tying with more than one wall at perpendicular joints to retain liquids, water storage and materials storages such as dyke walls and tanks. Retaining walls excessively used in culverts and as well as in the bridges i.e., construction of abutments, wing walls supposed to resist soil pressures, applied perpendicular to the axis of the walls. Due to insufficient land and based on the present construction scenario followed in the construction of retaining structures, the wall height is often increased, thereby increasing the cost of construction of sub structure. The values of the bending moment at the base increases due to the increase in the height of the wall resulting in higher sections which is uneconomical. The need of having safe and economical section shall be achieved by transforming the structural system of retaining wall i.e., by introducing supports to the vertical wall thus decreasing the thickness of stem. The design of rigid retaining wall either Cantilever or Counterfort or Buttress retaining wall is based on pressure exerted by the retaining material, wall slope, height, ease of construction and stability. When the retaining wall height is more than 8 m, the selection of extra supports i.e., either counterforts or buttresses is based upon the designer’s experience. By conducting comparative study on resisting forces for varying heights, the behaviour of these supports on retaining wall can be depicted. The depiction of forces can be achieved by running an analysis in STAAD.pro with preliminary dimensions and soil parameters respectively. Resisting forces from counterfort and buttress supports on retaining wall are equal when the height is in between 9 m to 24 m but buttress support has shown less resisting forces when the height is less than 9 m.

1. Introduction
Rapid increase in urbanization and industrialization is leading to the development of infrastructure in both onshore and offshore environments all over India. Construction of retaining wall is carried out in the infrastructural development activities like hillside farming or roadway overpasses, preventing soil erosion, aesthetic purposes and stabilizing sloped yards. A retaining wall is a structure designed and constructed to resist the lateral pressure of soil, when there is a desired change in ground elevation that exceeds the angle of repose of the soil [1]. Based on the availability and suitability of the material, there are two types of retaining walls i.e., Rigid and Flexible Retaining walls. Gravity, Cantilever, Counterfort, Buttress and Flexible retaining walls are categorized into Rigid type and reinforced Earth, anchored Retaining Walls are categorized into Flexible type.

The retaining wall is analysed based on soil pressure [2,9] and material properties [3,4] viz., angle of internal friction (Ø), Unit weight (λₜ) of the earth retained under static load conditions. Su Yang et. al., [11] has reviewed the various theories on dynamic/seismic condition based on...
experimental investigations and numerical findings subjected to dynamic excitations and proposed analytical, experimental or numerical findings that expose new aspects of wall behavior with a significant physical or mechanism basis in dynamic retaining wall design and analysis. S. S. Patil et. al., [5] stated that Cantilever retaining walls are economically suited for wall heights up to 6 m. When the height of earth retained is more than 8 m, extra supports named as counterforts or buttresses as shown in Figure 1-2 are introduced in order to avoid the failure either by overturning, sliding or tension. Swati Nagre et. al. [6] had concluded that stepped cantilever wall is more feasible than Gabion and Segmental type of retaining walls. Maen Farhat et. al., [7] had compared the design, structural efficiency, and structural performance between prefabricated counterfort retaining wall system and an existing counterfort cast-in-place concrete retaining wall system.

Patil, S. S. et. al., [12] has studied reduction of the stresses on the retaining face by introducing the steps and counterfort supports along the stem. Rupa B. Patil et. al., [13] designed and studied the variation of bending moment in stem wall of a counterfort retaining wall by varying the spacing of counterfort supports from 1 m to 4 m for non-cohesive soil condition. G. Madhavi et. al., [14] has conducted critical study on counterfort and buttress retaining wall with and without shear key for different backfill soils. Inder Kumar Lilani, et. al., [15] proposed a design solution by conducting a comparative study on the cost estimate for the optimal design between counterfort retaining wall and gravity wall in concrete dam. Sarita Singla et. al., [17] had done a comparative study on the behaviour and optimal design of cantilever & counterfort retaining wall with relieving platforms. Based on literature survey, it was observed that a lot of analysis had been carried out on the retaining walls and experts evaluated the cost economy, feasibility and structural performance of retaining wall with shear keys, relief shelves, but the criterion of selection of counterforts or buttresses as supports for cantilever retaining wall has not yet been studied in detail.

1.1. Objective of the study
This research is an attempt majorly focused on stating the suitability of supports i.e., counterforts as shown in Figure: 1 or buttress as shown in Figure: 2 for cantilever retaining wall with respect to height. This can be achieved by studying the estimated values of resisting forces and moments using STAAD.Pro software by varying heights from 3 m to 24 m assuming that retaining wall is stable under overturning, sliding and tension. Typical 3D model of counterfort retaining wall is shown in figure 3.

2. Literature study
Su Yang, Amin Chegnizadeh, Hamid Nikraz, 2013 considered two main streams of analytical solutions for the dynamic lateral earth pressure of retaining walls which are failure wedge equilibrium theory and Sub-grade modulus method. Based on the experimental data from a series of shaking table tests. Mononobe and Okabe [16] developed MO Method that combines Coulomb’s wedge equilibrium theory for determination of dynamic earth Pressures which was the main approach for the practical use due to its simplicity. The alternative way to the MO method for dynamic retaining wall analysis was the sub-grade modulus method where the soil-wall interaction is modeled by elements like springs with a stiffness modulus to relate displacement and generated pressure. The results from the elasticity
method are from 2.5 to over 3 times higher than those from widely used the MO approaches. Patil, S. S., and A. R. Bagban, 2015 conducted cost comparison between cantilever & counterfort retaining wall and stated that former is economically suited for wall heights up to 6.0 m and later for the heights 8.0 m to 10.0 m for assumed site conditions assumed.

G. Madhavi and M.M. Mahajan, 2016 concluded that the effect shear key and relief shelve would decrease the stresses in the counterfort retaining wall and also found that optimum location of relief shelf shall be at 2/3rd height from the top of the wall. Comparing the provision of number of relief shelves along the height, it was resolved that provision of two shelves is advantageous if the height of counterfort retaining wall is more than 8 m. Inder Kumar Lilani,

Dr. Rakesh Patel, 2017 stated that the concrete quantity in the spillway of the dam can be reduced, if counterfort retaining wall is chosen as overflow section and gravity retaining wall is chosen as non-overflow section. Sarita Singla and Sakshi Gupta, 2015 stated that the retaining wall with relieving platform is proved to be most cost effective and advantageous over the cantilever and counterfort retaining wall. Moreover, Sarita Singla et. al., stated that there is a better stability in the retaining wall due to discontinuous lateral earth pressure diagram with relieving platform. Reduction in cross-sectional in retaining wall with relieving platforms area reduces the requirement of the construction material and overall cost.

3. Methodology

3.1. Preliminary Dimensions

The cantilever, counterfort and buttresses retaining wall models has been developed with preliminary dimensions referring Krishna Raju [10] with respect to the overall height (H) i.e., models are developed for every 3 m interval up to 24 m as specified in first column of Table 1. The base slab width and thickness, toe and heel projections and stem thickness are stated below:

a) Cantilever retaining wall:
   1. The width of the base slab is kept about 2H/3.
   2. The width of the stem at bottom, the thickness of the base slab and the length of the toe projection, each is kept about 0.1H.

b) Counterfort retaining wall
   1. The counterforts are about 0.3 m thick with centre to centre spacing of 0.3H to 0.7H
   2. The thickness and width of base slab is taken as H/12 and 0.55H respectively
   3. The projections at toe and heel are H/6 and 3H/10 and thickness of stem as H/12

c) Buttress retaining wall
   1. The centre to centre spacing of counterfort (L) is taken as 0.3H to 0.7H
   2. The thickness and width of base slab is taken as 20LH and 0.65H respectively
   3. The projections at toe and heel are (¼)B and 3H/10 and thickness of stem as 20LH

3.2. Soil properties

The Earth pressure based on assumed soil parameters stated below was estimated with reference to Y. Z. Wang [9]

1. Angle of internal friction= 30°
2. Safe bearing capacity of the soil (SBC) = 200 KN/sqm
3. Unit weight of the soil w = 18 KN/cum.
4. Depth of foundation at heel portion for heel slab is given in [Equation 1]

\[
\text{Depth of Foundation} = \frac{\text{SBC}}{w} \times \left( \frac{1 - \sin \varphi}{1 + \sin \varphi} \right)^2 - \text{[Equation 1]} 
\]

3.3. Material, Modelling & Analysis

In this study, isotropic concrete of compressive strength 30 MPa with density 23.5 KN/cum was assumed. As per preliminary dimensions, nodes are generated and plate elements are assigned. Further, quadrilateral meshing was adopted to get stress strain contours and bottom nodes are assigned as fixed supports. Typical stress contour and loading diagram is shown in Figure 4 and Figure 5
respectively. Based on the height of the retaining wall, the earth pressure on stem and dead load above heel slab was calculated and applied to assess the forces.

![Figure 4. Principal Stress Contour](image)

![Figure 5. Supports and loading diagram](image)

4. Results and Discussions

The resisting forces $F_x$, $F_y$, $F_z$ in KN and resisting moments $M_x$, $M_y$, $M_z$ in KN-m for cantilever retaining wall are shown in Table 1 and are compared with counterfort and buttress retaining wall.

| Height, $H$, m | $F_x$, KN | $F_y$, KN | $M_x$, KN-m | $M_y$, KN-m | $M_z$, KN-m |
|---------------|-----------|-----------|-------------|-------------|-------------|
| 3             | -750.87   | -1104.46  | 4970.08     | -3378.91    | -464.82     |
| 6             | -4004.64  | -10451.4  | 62708.31    | -24027.8    | -16488.1    |
| 9             | -11263.1  | -42231.2  | 316734.3    | -84472.9    | -118217     |
| 12            | -24027.8  | -117458   | 1057123     | -216251     | -474618     |
| 15            | -43800.8  | -264038   | 2772397     | -459908     | -1396862    |
| 18            | -72083.5  | -516626   | 6199507     | -865002     | -3381215    |
| 21            | -110378   | -916883   | 12377917    | -1490101    | -7153037    |

The comparison of forces and moments of counterfort retaining wall (CRW) and buttress retaining wall (BRW) in percentile with respect to cantilever retaining wall as per Table 1 are estimated and are shown in Table 2. The same are plotted in Figure 6, 7, 8.

| Height, $H$, m | $F_y$, KN CRW | $F_y$, KN BRW | $M_y$, KN-m CRW | $M_y$, KN-m BRW | $M_z$, KN-m CRW | $M_z$, KN-m BRW |
|---------------|----------------|----------------|-----------------|-----------------|-----------------|-----------------|
| 3             | 6.14           | 7.68           | 15.75           | 12.8            |
| 6             | 3.24           | 4.43           | 4.44            | 3.67            |
| 9             | 2.16           | 1.05           | 2.5             | 0.4             |
| 12            | 1.61           | 0.79           | 1.72            | 0.28            |
| 15            | 1.32           | 1.11           | -1.11           | -0.73           |
| 18            | 1.06           | 0.52           | 1.05            | 0.17            |
| 21            | 0.9            | 0.44           | 0.88            | 0.14            |
| 24            | 0.78           | 0.56           | 0.75            | 0.42            |
From Figure 6 it shall be noted that percentage variation of support reactions of buttress and counterfort retaining wall trail a constant trend line when height is from 9 m to 24 m. It can also be depicted that when the height of the wall is less than 9 m counterforts are best suitable rather than buttresses as supports to cantilever retaining wall.

From Figures 7 & 8 it shall be noted that the percentage variation in moments i.e., in x and z directions for counterfort supports shown increasing trend up to 3 m and then shown a decreasing trend up to 9 m whereas in the case of buttress supports an opposite trend has been observed which reveals that counterfort supports are better suitable for cantilever retaining walls when the height is within 3 m to 9 m. Adding, a constant trend line is observed when the height of the retaining wall is varying from 15 m to 24 m which reveals that both counterforts and buttress supports shall be are suitable.

5. Conclusion
Using STAAD.pro software depiction of forces and moments from cantilever retaining wall with buttress or cantilever supports have been analysed and evaluated by plotting the changes in values of same in percentage. The forces are drawn assuming that the retaining wall is stable and supports are rigid so as to eliminate the complexity of induced lateral force.

From the obtained results, it can be drawn to a conclusion that the both buttress and counterfort supports on retaining wall follows the same trend line when height is between 9 m to 24 m.
In addition, if the retaining wall height is between 15 to 21 m, buttress supports are suitable than counterfort support. Moreover, if the height of the retaining wall is less than 9 m, counterfort supports are more suitable rather than buttress supports.

6. Limitations and Future Scope
This study may be helpful in making a decision whether to adopt buttress support or counterfort supports when the retaining wall height is from 3 m to 27 m. Although conclusion has be drawn for the suitability of the support, further studies can be done on spacing of supports in longitudinal direction and preliminary dimension aspects.

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