Influence of shelf placement and backfill materials on the structural Behaviour of retaining wall: A finite element approach

Pooja verma[1], Ankit Raj Nirala[2], Dr. R. N. Khare[3]
[1]M TECH Scholar(structural engineering)VEC Ambikapur, C.G

[2]Assistant Professor, Department of Civil Engineering, VEC Ambikapur, C.G.

[3]Principal, VEC Ambikapur, C.G

Abstract: This study investigates the structural performance of retaining walls with shelves, focusing on deformation, earth pressure distribution, and the influence of various backfill materials. Using finite element analysis, three distinct configurations were analyzed: a retaining wall without shelves, a wall with shelves using dolomite as the backfill, and a wall with shelves using tight gas sandstone as the backfill. The results revealed that retaining walls without shelves exhibited significant deformation (257.8 mm), with maximum earth pressures reaching 85.07 MPa at the bottom corner. In contrast, retaining walls with shelves showed reduced deformation (159.97 mm and 134.98 mm, respectively), indicating improved stability. The earth pressure distribution for walls with shelves was more uniform, with maximum pressures of 6.2615 MPa (dolomite) and 4.65 MPa (sandstone), highlighting the effect of shelf placement and material choice. A comparative analysis of horizontal and vertical earth pressures revealed distinct patterns of pressure distribution, especially at different depths, and emphasized the importance of shelf positioning in altering pressure behavior. Additionally, the study explored the impact of varying shelf depths on earth pressure, demonstrating that increasing shelf depth can significantly affect pressure distribution. The findings provide critical insights into the design of retaining walls, offering recommendations for optimizing shelf placement, backfill material selection, and overall wall stability. Future research could extend these findings by incorporating dynamic loading, advanced optimization techniques, and the use of smart monitoring systems to enhance the design and performance of retaining walls in diverse environmental conditions.

Key Words: *Retaining wall, stability*

1. INTRODUCTION:

Retaining walls are structural systems widely employed in civil engineering to resist lateral pressures of soil or other materials in areas with abrupt elevation changes. These structures serve crucial roles in infrastructure development, such as supporting roads, railways, basements, and landscapes. The primary purpose of retaining walls is to maintain soil stability and prevent erosion or collapse in areas with slope modifications or excavation activities. Traditionally, retaining walls have been constructed using various materials and designs such as gravity walls, cantilever walls, counterfort walls, and mechanically stabilized earth walls. Each type is selected based on soil characteristics, environmental loads, height, and economic considerations. An important factor influencing retaining wall behavior is the choice of backfill material, which determines the magnitude and distribution of earth pressure acting on the wall. Modern engineering practices emphasize sustainable design and performance-based analysis, often requiring an in-depth understanding of complex soil-structure interactions. To this end, the Finite Element Method (FEM) has emerged as a powerful computational tool for modeling and analyzing retaining wall systems under varied loading and boundary conditions. FEM simulations allow for detailed insights into stress distribution, deformation, and the effects of material properties, geometry, and external forces.

2. LITERATURE REVIEW

Arulrajah et al. (2012) This study focused on **soil-**structure interaction (SSI) and its critical influence on retaining wall performance under dynamic conditions. Using finite element analysis (FEA), the researchers demonstrated that incorporating SSI leads to more accurate predictions of wall displacement and stress behavior than traditional models. Their findings reinforced the necessity of realistic simulation techniques in retaining wall design.

Donkada et al. (2012) This study laid foundational principles by explaining the mechanics of lateral earth pressure—active, passive, and at-rest—crucial for any retaining wall design. They also stressed the importance of understanding backfill properties, wall height, and water table levels. The researchers highlighted that overlooking wall-soil friction and adhesion can lead to unsafe structures.

Agusti and Sitar et al. (2013) Agusti and Sitar investigated the role of groundwater in increasing lateral earth pressures acting on retaining walls. Their research emphasized that ignoring hydrostatic pressures from elevated water tables can lead to underestimations in design, risking sliding or overturning failures. They advocated for integrated drainage systems and waterproofing solutions to control subsurface water effects, ensuring structural safety.

C. Sanjei et al. (2015) Sanjei and colleagues explored how temperature variations affect reinforced concrete retaining walls. Seasonal changes cause thermal expansion and contraction, which can induce additional stresses and cracking. The researchers recommended design elements such as expansion joints and flexible materials to mitigate thermal effects, particularly in regions with high temperature fluctuations.

Inder Kumar et al. (2017) The role of backfill materials was further examined by Inder Kumar et al., who emphasized the advantages of using cohesionless soils like sand and gravel. These materials, when well-compacted, enhance wall stability and drainage. The study underscored that improper backfill gradation or moisture retention leads to excessive settlement and lateral pressure buildup.

D.R. Dhamdhere et al. (2018) Dhamdhere's work centered on sustainable engineering practices in retaining wall construction. By integrating recycled aggregates and vegetated facades, the study presented environmentally friendly solutions that also reduced lifecycle costs. These green methods offered both aesthetic and functional improvements, including better drainage and erosion resistance.

3. OBJECTIVES

The objective of current research is to optimize the design of retaining wall using response surface optimization technique. The 3D model and structural analysis of retaining wall is developed in ANSYS simulation package. The optimization method used in the research is optimal space filling design.

4. METHODOLOGY

The figure 1 illustrates the 3D geometry of a retaining wall system developed using ANSYS Design Modeler as part of the finite element simulation process. The model incorporates key structural and geotechnical components essential for analyzing soil-structure interaction. The retaining wall is shown embedded in a soil mass, with a triangular backfill zone represented in green, simulating the retained earth. The backfill is inclined, which reflects a typical slope or embankment scenario often encountered in field conditions. This inclination is crucial for simulating realistic lateral earth pressures exerted on the wall. The base of the wall extends laterally, forming a footing structure that anchors the wall and resists sliding and overturning moments. The surrounding domain includes a sufficient soil volume to minimize boundary effects during simulation, ensuring accurate stress and displacement field development.

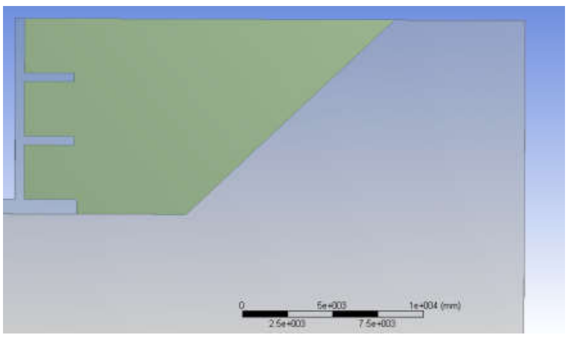

Figure 1: 3D model of retaining wall with shelves

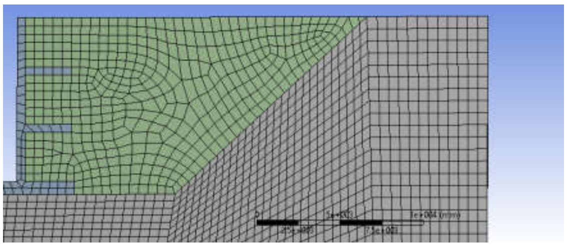

Figure 2: Meshed model of retaining wall

The retaining wall model is discretized using fine relevance settings. The model is meshed using tetrahedral element type and hexahedral element type. The model growth rate for meshing is set to 1.2 and inflation is set to normal.

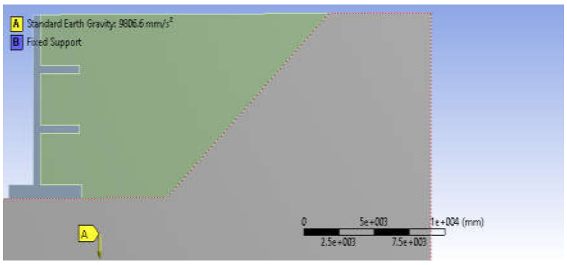

Figure 3: Loads and boundary conditions

After discretization, the structural loads and boundary conditions are defined for the model. The structural boundary conditions include fixed support at the base and standard earth gravity for the entire structure. After applying structural boundary conditions, the simulation is run. During the simulation process, the matrix is formulated for every element. The nodal calculations are performed and the obtained results are interpolated for entire element edge length.

4. RESULTS AND DISCUSSION

The contour plot above illustrates the stress distribution in a retaining wall structure subjected to lateral earth pressure, obtained from a static structural analysis performed using finite element software. The analysis was conducted in the global coordinate system at time step 1. The color gradient indicates varying levels of stress, with red regions showing the highest compressive stresses (up to 2.463 MPa) and dark blue areas representing the lowest or most tensile stress values (down to –4.371 MPa). It is evident that the highest stress concentrations occur near the base and the interface between the retaining wall and the backfill soil, particularly around the wall stem and the toe region. These regions are critical in design, as they are subjected to the maximum loading and thus dictate the structural integrity of the wall.

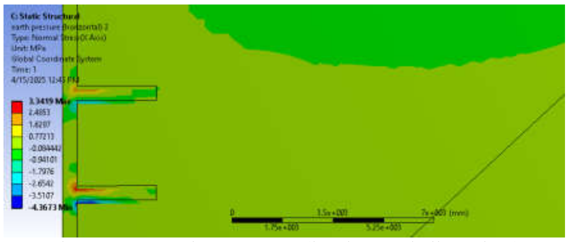

Figure 4: Earth pressure (horizontal direction)

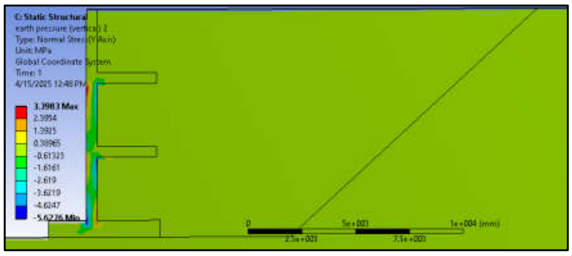

Figure 5: Earth pressure (vertical direction)

The stress values range from a maximum of 3.198 MPa (in red) to a minimum of –4.524 MPa (in dark blue), indicating significant compressive and tensile zones. The stress concentration is most prominent along the back face of the retaining wall near the base, as well as in the regions of wall-soil interaction, especially at the heel and toe. These high-stress zones suggest areas of structural importance requiring reinforcement or design optimization. The overall stress pattern reflects the typical behavior of a retaining wall resisting soil pressure, where the maximum compressive forces act at the bottom portion of the wall. The relatively uniform distribution in the backfill area suggests a consistent application of lateral pressure. The inclusion of support structures such as counterforts or key extensions appears to influence the stress field, providing additional stability and load distribution. This result supports the design assumption that lateral earth pressure is not uniformly distributed and varies significantly along the height and base of the wall. It is essential to consider these variations for safe and economical retaining wall designs.

Table 4.1: Comparison table

Backfill Type	Vertical Earth Pressure Trend	Horizontal Earth Pressure Trend	Maximum Pressure Value	Notable Observations
Dolomite	Exponentially increases, peaks at 9375 mm, then decreases	Gradual increase, peaks at 2.39 MPa at 10,000 mm (base of the wall)	2.39 MPa (horizontal component)	Backfill with high stiffness; shelves reduce pressure temporarily before increasing again
Sandstone 1	Irregular; increases, then drops near shelves, and rises again—especially at depths like 6458.3 mm	Gradual increase with depth, drops near first shelf, then increases again, peaking at 1.731 MPa at base	1.731 MPa (horizontal component)	Shelves cause disruptions in pressure distribution; less dense material shows more sensitivity to structural interruptions like shelf placement

Response Surface Optimization

The Design of Experiments (DOE) chart obtained using the response surface method (RSM) with an optimal space-filling design provides valuable insights into the relationship between various design parameters and the resulting performance metrics of the retaining wall system. In this case, the chart includes three factors shelf thicknesses (P1 and P2), horizontal earth pressure (P6), vertical earth pressure maximum (P9), and total deformation maximum (P10) across a set of design points (1 to 9). For k factors, each at n levels, the total number of experiments is:

$$N=n^k$$

General Factorial Model Equation is given by:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \epsilon$$

β_0: Intercept

β_i: Linear effect of factor xi

β_{ii}: Quadratic effect of factor xi

β_{ij}: Interaction effect between factors x_i and x_j

ϵ: Random error

Table 4.2: Design of Experiments Table

Design Points	P1 - shelve_thicknes s1 (mm)	P2 - shelve_thicknes s2 (mm)	P6 - earth pressure (horizontal) (MPa)	P9 - earth pressure (vertical) Maximum (MPa)	P10 - Total Deformation Maximum (mm)
1	522.2	466.6	3.328	3.462	125.353
2	544.4	488.8	3.489	3.484	125.372
3	477.7	522.2	3.342	3.326	125.372
4	511.1	511.1	3.342	3.421	125.343
5	466.6	455.5	3.325	3.316	125.416
6	488.8	477.7	3.324	3.376	125.381
7	500	544.4	3.252	3.373	125.390
8	533.3	533.3	3.284	3.451	125.362
9	455.5	500	3.323	3.259	125.406

The shelf thicknesses, represented as P1 (shelve_thickness1) and P2 (shelve_thickness2), are varied between 455.56 mm and 544.44 mm across different design points. These variations in thicknesses influence the distribution of earth pressure and deformation on the retaining wall. For example, design point 7 has the largest variation in shelf thickness (P1 = 500 mm, P2 = 544.44 mm), whereas design point 5 has a more balanced configuration (P1 = 466.67 mm, P2 = 455.56 mm). These changes in shelf configurations can have a notable impact on the earth pressures and the overall stability of the retaining wall structure. The horizontal earth pressure (P6) varies from 3.2529 MPa (design point 7) to 3.4893 MPa (design point 2). This suggests that small adjustments in shelf thickness can influence the horizontal pressure exerted on the retaining wall. Design point 2, with a higher horizontal earth pressure, reflects the influence of slightly thicker shelves at both positions (P1 = 544.44 mm, P2 = 488.89 mm), likely contributing to a more substantial earth load on the wall. The vertical earth pressure shows a smaller range of values, from

3.2599 MPa (design point 3) to 3.4844 MPa (design point 2). It indicates the effect of varying shelf thicknesses on the vertical pressure distribution. Design points with closer shelf thickness values (like design point 8, P1 = P2 = 533.33 mm) generally result in pressures closer to the mean value, while configurations with different thicknesses (like design point 2, P1 = 544.44 mm, P2 = 488.89 mm) produce higher pressures at the base of the wall, possibly due to an imbalance in load distribution. The total deformation maximum, represented as P10, ranges from 125.2529 mm (design point 7) to 125.41697 mm (design point 5). The small variation in deformation values suggests that the retaining wall structure is generally stable across the range of design points, with minimal influence from shelf thickness variations. This may imply that while shelf thickness affects earth pressure distribution, the overall structural deformation remains relatively consistent across different configurations.

- **Impact of Shelf Thickness**: Varying the shelf thickness has a more noticeable effect on horizontal and vertical earth pressures than on total deformation. The most significant variation in horizontal pressure occurs at design points where there is a larger difference between P1 and P2, such as in design points 2 and 7.
- **Pressure Distribution**: Both the horizontal and vertical earth pressures are sensitive to the shelf thickness configuration, with some design points leading to higher maximum pressures, particularly at the bottom of the retaining wall.
- **Total Deformation**: While the deformation remains relatively stable across all design points, the consistent deformation values suggest that the retaining wall structure is adequately designed to withstand the applied pressures without significant failure or excessive deformation.

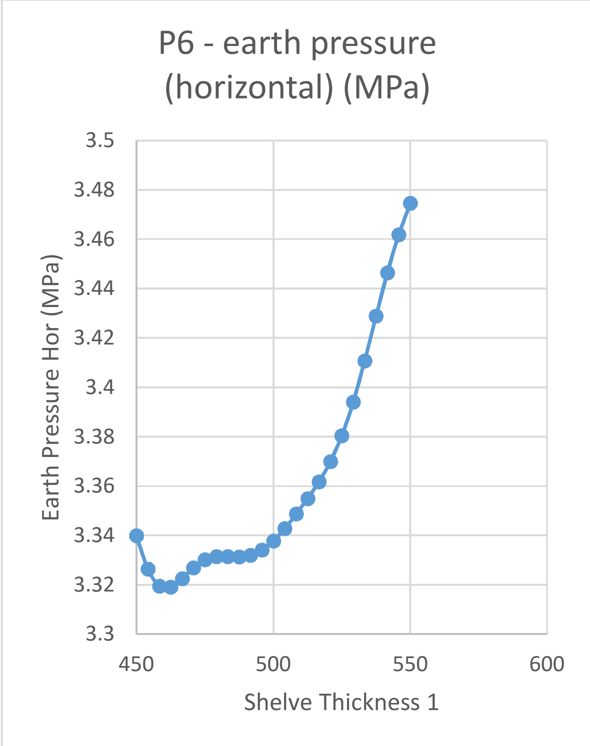

Figure 6: Earth pressure (horizontal) vs shelve_thickness1

The relationship between shelf thickness (P1) and horizontal earth pressure (P6) is observed from the given dataset, where the shelf thickness ranges from 450 mm to 550 mm, and the corresponding horizontal earth pressure varies from 3.3399 MPa to 3.4746 MPa. The horizontal earth pressure (P6) demonstrates a generally increasing trend as the shelf thickness (P1) increases. This relationship indicates that the shelf thickness plays a significant role in the distribution and magnitude of horizontal earth pressure acting on the retaining wall. For lower values of shelf thickness (450 mm to 470.83 mm), the horizontal earth pressure remains relatively stable, varying slightly between 3.3399 MPa and 3.3269 MPa. This minimal change suggests that for thinner shelves, the earth pressure is less sensitive to incremental increases in shelf thickness.

5. Conclusion

The analysis of the retaining wall structure with and without shelves has provided valuable insights into its stability, stiffness, and overall structural performance. The inclusion of shelves significantly enhances the wall's ability to distribute earth pressure more evenly, reducing deformation and improving its resistance to overturning and sliding. By optimizing the pressure distribution, especially in the lower regions of the wall, the design with shelves demonstrates better control over both vertical and horizontal earth pressures. The findings also indicate that the depth and placement of the shelves play a crucial role in managing earth pressure, further enhancing stability and reducing risk. The choice of backfill material, such as dolomite or tight gas sandstone, also influences the performance, with stronger materials contributing to better stability and reduced deformation. Overall, the retaining wall with shelves shows improved stiffness, better resistance to dynamic loads, and enhanced safety margins, ensuring the long-term durability and stability of the structure under varying environmental conditions and applied loads.

1. The inclusion of shelves in the retaining wall design leads to improved stability, as evidenced by the reduced total deformation values (159.97 mm with shelves vs. 257.8 mm without shelves), signifying that shelves help distribute the applied earth pressure more evenly across the wall, thereby preventing localized failure.

2. The strategic placement of shelves effectively reduces the maximum earth pressure at critical points, especially at the bottom corner, thus lowering the likelihood of overturning. The analysis indicates that the maximum earth pressure at the base is lower in walls with shelves, compared to those without shelves, minimizing the overturning risk.

3. The retaining wall with shelves exhibits increased stiffness as demonstrated by the lower deformation values and a more controlled distribution of pressure, enhancing the wall’s ability to resist displacement under both static and dynamic loads. This increased stiffness contributes to a more rigid structure that can withstand applied forces without excessive deflection.

4. The DOE analysis highlights that with shelves, both the vertical and horizontal components of earth pressure are more evenly distributed along the wall, which reduces concentrated pressures at the base. This optimized pressure distribution enhances overall structural performance and reduces the risk of failure due to high localized stress.

5. The depth of the shelves plays a significant role in controlling the distribution of pressure and improving the overall stability of the retaining wall. Deeper shelf placements reduce the maximum earth pressure at the base of the wall, thus lowering the potential for failure and ensuring better resistance to overturning.

6. The deformation of the retaining wall is substantially reduced with the inclusion of shelves, showing that shelves help in improving the structural integrity of the wall. The lower deformation values indicate that the structure is more stable and less prone to failure under the given load conditions.

7. The type of backfill material (e.g., dolomite, tight gas sandstone 1) has a significant impact on the overall stability and stiffness of the retaining wall. Backfill materials with higher strength and compaction contribute to improved pressure distribution and reduced deformation, enhancing the overall stability of the wall.

8. The introduction of shelves helps mitigate excessive horizontal earth pressures, particularly in areas near the bottom of the retaining wall. The DOE data indicates that horizontal pressure is more evenly distributed with shelves, reducing the risk of sliding and contributing to the structural stability of the wall.

9. The vertical component of earth pressure increases exponentially with depth, and the presence of shelves helps moderate this increase. This allows the wall to better manage high vertical pressures, ensuring stability at greater depths and preventing excessive deformation or structural failure.

10. By redistributing the applied earth pressure and enhancing the overall stiffness, the shelves also improve the wall's resistance to sliding. The pressure reduction at the base of the wall, particularly in the design with deeper shelves, lowers the shear forces acting on the foundation, thus reducing the potential for sliding failures.

Future scope

Future studies could explore further optimization of shelf placement and depth to better distribute earth pressure and minimize deformation, particularly under varying load conditions. Investigating the use of advanced or engineered backfill materials could provide improved stability and reduce the overall deformation, enhancing the retaining wall's performance. Further research can focus on the seismic analysis of retaining walls, especially in areas prone to earthquakes, to understand the dynamic behavior of retaining walls with shelves under seismic loading.

REFERENCES

[1] Agusti, A., & Sitar, N. (2013). Influence of groundwater on retaining wall performance. *Journal of Geotechnical Engineering*.

[2] Arulrajah, A., et al. (2012). Dynamic effects of soil-structure interaction on retaining walls. *Geomechanics and Engineering*.

[3] Sanjei, C., et al. (2015). Thermal influence on retaining wall behavior. *Construction and Building Materials*.

[4] Dhamdhere, D.R., et al. (2018). Sustainable materials in retaining wall construction. *Environmental Geotechnics*.

[5] Donkada, S.R., et al. (2012). Understanding lateral earth pressure for wall design. *Soil Mechanics Journal*.

[6] Kumar, I., et al. (2017). Effects of backfill selection on retaining wall stability. *International Journal of Civil Engineering*.

[7] Mikola, R.G., et al. (2013). Expansive soil management in wall foundations. *Canadian Geotechnical Journal*.

[8] Abood, T., et al. (2015). Role of drainage in the safety of retaining walls. *Journal of Civil Infrastructure*.

[9] Chaliawala, Y., et al. (2015). Application of numerical modeling in retaining wall analysis. *Engineering Structures*.

[10] Ozaki, T., Nakajima, S., 2021. Centrifuge model test on seismic active earth pressure acting on retaining wall with cohesive backfill soil. Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney, In press

[11] S. S.Patil and A. A. R. Babgan, "analysis and design of reinforced concrete stepped cantilever retaining wall", IJRET, vol. 04, Feb-2015, page 46-67

[12] Rupa B. Patil, G. R. Patil, "Design and detailing of counter fort retaining walls for construction site", International journal of informative & fururistic research, Vol. 3, September 2015, page 61-71