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EFFECT OF SOIL STRUCTURE INTERACTION ON REINFORCED CONCRETE RETAINING WALL

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Abstract - *In this study, the interaction between soil and structure is a critical aspect influencing the performance and stability of reinforced concrete retaining walls. This study investigates the effects of soil‑structure interaction on such walls, aiming to enhance understanding and design methodologies. The interaction is examined through comprehensive analyses considering factors like soil type, wall geometry, and reinforcement details. Key parameters such as lateral earth pressure distribution, wall deflection, and overall stability are evaluated to ascertain how soil properties and structural design choices impact performance. Findings highlight the significance of integrated design approaches that consider both soil behavior and structural response, ensuring resilient and efficient retaining wall systems suitable for various environmental conditions and loading scenarios.*

Key Words: Soil-structure interaction, Retaining walls, Finite element method (FEM), Stability, Lateral earth pressure.

1. INTRODUCTION

Retaining walls, such as Counterfort Retaining Walls (CRWs), are fundamental in civil engineering for supporting soil and managing changes in ground elevation. CRWs utilize counterforts on the backside to enhance stability and are typically built using materials like plain cement concrete or occasionally stone and brick masonry. Designing these walls requires careful consideration of potential failure modes: sliding, overturning, excessive settlement, and scour. Sliding occurs when soil moves horizontally along the base due to insufficient friction, making it a critical design factor. Overturning is prevented by ensuring the foundation and counterforts can withstand the moments caused by soil pressure. Settlement issues are managed through rigorous soil analysis and proper foundation design to minimize uneven settling. Furthermore, measures against scour, such as effective drainage and protective barriers, are crucial for maintaining the wall's stability over time. Engineers strive to optimize the cross-sectional design to ensure materials are efficiently used and the structure remains resilient against these challenges. This approach ensures CRWs not only meet immediate construction needs but also provide long-term reliability and safety across various engineering projects.

1.1 Aim & Objective

To find the effect of Soil Structure Interaction on counterfort retaining wall based on Geometrical & geotechnical parameters.

The following are the objective of research work,

Exclusive literature review is carried out and the unfocused area is identified which is consider as problem for proposed dissertation. The effect of soil structure interaction on counterfort retaining wall is proposed to carried out using following points,

- Analysis counterfort retaining wall sections for various heights & various loading condition.
- Finite Element analysis of above-mentioned faces with and without soil structure interaction for counterfort retaining wall.
- Identify the parameters influenced by soil structure interaction and develop non-dimensional chart for finding effect of soil structure interaction for geometrical & geotechnical parameters.

2. Literature Review

Soil Structure Interaction (SSI) for Cantilever Retaining Walls elucidates the intricate relationship between the structural element and the surrounding soil, highlighting the significance of understanding how external forces acting on the wall and internal forces within the ground mutually influence each other. This interdependence underscores the importance of considering soil-structure interaction in the design and analysis of counterfort retaining walls to ensure their stability and effectiveness in supporting soil masses and resisting external loads.

Contributions of researchers are presented as follows,

Sunil Gupta, Tsung-Wu Lin, Joseph Penzien, Chan-Shioung Yeh [1] described a hybrid model for the analysis of soil-structure interaction proposed which promises to be superior to the 19th time methods of analysis. The modelling achieved by partitioning the total soil-structure system into a near field and a far field with hemispherical interface. The near field consists of the structure, which analyzed and a finite region of soil around it was modelled by the finite element method. For the semi-infinite far field, impedance matrix corresponding to the interface degrees of freedom developed which accounts for the loss of energy due to waves travelling away from the foundation.

Robert M. Ebeling [2] presented a review of previous work in which the finite element method was used to analyze the soil-structure interaction of earth retaining structures such as U-frame locks, Gravity Retaining Walls, and basement walls. This method of analysis resulted in the computation of stresses and displacements for both the structure and the soil backfill. Applications of the procedure showed the importance of modeling the actual construction process as closely as possible and the use of a nonlinear stress-strain soil model. Additional requirements included modeling the interface between the soil backfill and the wall, which used interface elements. He also included two recent applications of the finite element method for the analysis of earth retaining structures, which was loaded so heavily that a gap developed along the interface between the base of the structure and its foundation.

Timothy D. Stark, Steven M. Fitzwilliam, Joseiph J. Vettel, Robert M. Ebeling [3] described Soil-Structure Interaction Parameters for Silts. They tried to characterize the drained and undrained stress-strain behavior of normally consolidated silts and clayey-silts. They used the result of their research to develop a database of hyperbolic stress-strain and Mohr-Coulomb strength parameters for silts and clayey-silts. They carried out extensive drained and undrained triaxle tests on silt specimens with varying clay contents. They used percentages of clay in the silt mixtures were 0, 10, 30, and 50%. "The effect of density was investigated by compacting the triaxle test specimens at Standard Proctor relative compactions of 85, 90, 95, and 100%. They summarize the test results and the resulted hyperbolic stress-strain and Mohr-Coulomb strength parameters for the various silt mixtures considered.

T. Kupsmy, Mark A. Zarco [4] in this Study described the finite element computer program SOILSTRUCT used in the evaluation of soil structure interaction of earth retaining structure.

Mete Oner, William P. Dawkins [5] conducted a comprehensive analysis procedure to understand the soil structure interaction, mechanism involved in behavior of floodwall systems. They used finite element method with suitable model of the soil structure interface, nonlinear soil behavior, and loading sequence. On test section, they used an existed floodwall for verification of analytical model.

Eduardo Kausel [6] Describes early history of soil–structure interaction. The early history of Soil Structure Interaction which lies at the intersection of soil and structural mechanics, soil and structural dynamics, earthquake engineering, geophysics and geo-mechanics, material science, computational and numerical methods, and diverse other technical disciplines.

Dr. S. A. Halkude, Mr. M. G. Kalyanshetti, and Mr. S. H. Kalyani [7] the author worked on study of Soil Structure Interaction Effect on Seismic Response of R.C. Frames with Isolated Footing. The author investigated the effect of soil flexibility on the performance of building frame. Two SSI modes was considered for the analysis; one replaced soil by spring of equivalent stiffness (Discrete Support) and second by considered the whole soil mass (Elastic Continuum). Symmetric space frames rested on isolated footing of configurations 2 bay 2 storey (2X2X2), 2 bay 5 storey (2X2X5) and 2 bay 8 storey (2X2X8) was considered with fixed base and flexible base. The spring model was developed by using stiffness equation along all 6 DOF and elastic continuum model was developed by Finite Element Method using SAP-2000. For SSI study three types of soil was considered i.e. Hard, Medium Hard and Soft Soil. The dynamic analysis was carried out using. Response Spectrum, given in IS1893-2002. The influence of soil structure interaction on various structural parameters i.e. natural time period, base shear, roof displacement, beam moment and column moment was presented. The study reveals that the SSI significantly effects on the response of the structure. Finite Element Method has proved to be the effective method for consideration of elastic continuum below foundation.

K. Senthil, M. A. Iqbal & Amit Kumar [8] Author had worked on three-dimensional (3D) finite element simulations performed in order to study the response of cantilever and counterfort retaining walls subjected to lateral earth pressure using ABAQUS/Standard. Four retaining walls with different geometrical configurations was analyzed including three cantilever and one counterfort wall. The obtained results compared, and the mechanics involved in the behavior of the retaining wall was discussed. The lateral displacement, vertical settlement, and stresses developed in each component of the retaining wall was studied and compared with the other walls. The choice of the retaining wall based on the economic analysis was also discussed and compared.

Dr. P. P. Tapkire [9] in this research work author had worked on Optimization of gravity retaining wall profile by introducing cavity. In which the main aim of this paper was to develop a cost effective and structurally efficient profile of gravity retaining wall by introducing cavity in the section. For this, various section sizes of gravity retaining wall was analyzed and accordingly profile was selected and then after selection of an appropriate profile of gravity retaining wall stability calculations was carried out for various heights using „C" programming by strength of material approach.

Ms. Patil Swapnal V. [10] in this study, Effect of Soil Structure Interaction on Gravity Dam. The effect on gravity dam had been examined using finite element analysis software ANSYS 14. The gravity dam completely resting on soil media and surrounded by soil media. The relevant amount of soil around and bottom of the gravity dam had been modeled to simulate the in-situ conditions. The gravity dam was analyzed using dynamic loading in transient analysis using Imperial Valley (1940) earthquake record was included. Analysis of the gravity dam carried out and the influence of soil properties studied at the region of transverse sections, which exhibited the response in terms of stress and deformation with significant difference.

Snehal R. Lahande [11] Analytical Study of Cantilever Retaining Wall Including Effect of Soil Structure Interaction. The influence of the different types of soil on the different heights of the wall was addressed. A cantilever retaining wall was considered and modeled for the soil-structure interaction using finite element package SAP2000 Version 14.0.0. Dynamic distress and response of a cantilever retaining wall was studied considering six degrees of freedom system. For the validation purpose of the retaining wall, support conditions were considered to be fixed. For the analysis, the inputs are density of concrete, modulus of elasticity of concrete, density and SBC of soil, modulus of elasticity of soil, angle of internal friction and loading (active and passive earth pressure). The targeted output was maximum lateral displacement. The response spectrum inputs were given to the retaining wall for all the three types of soils (soft, medium, soft rock and hard rock) and three types of seismic zones (III, IV and V). After the analysis, it was observed that the percentage variation in the deflection is 900% (avg) towards the fixed end and converges to 1% towards the free end when compared with classical method. As the stiffness of the soil increases there was a reduction in deflection and as the height of the retaining wall increases there was an increase in the deflection at their free ends. The deflection increases with the increase in seismic zone value.

Eko Tavip Maryanto, Rezza Ruzuqi, and Victor Danny [12] The authors have worked on Strength Analysis of Soil Retaining Wall Using Numerical Method of Manokwari Landfill. The author investigated that the mechanical effects of soil retaining wall in the three types of designs of the landfills by 2D finite element analysis. The results could provide a reference for building to withstand the active lateral compressive forces of soil and water. The contribution of this study was sufficient for providing a functional strength of retaining walls. FEM (Finite Element Method) used in analyzing the compressive strength of retaining wall. The researcher used 2D analysis to determine the compressive strength of the soil on the retaining wall of the landfill in Manokwari City. The retaining wall in this study was varied based on these three forms of the retaining wall. According to the literature and the three different finite element numbers based on the software. Ansys software was used to simulate the compressive strength of retaining walls against the ground. The results found and compared. The results obtained indicated that the geometry design 2 had a better safety value when compared to the others.

3. Problem formulation

Structural engineering and geotechnics are intertwined disciplines essential for the accurate analysis of civil engineering structures. Effective soil-structure interaction (SSI) modeling is vital to capture the real behavior of both the superstructure and subgrade. Structural engineers often use detailed models for structures but simplify the subgrade, while geotechnical engineers use advanced soil models with simplified structures. Combining advanced models from both fields would demand unrealistic computation times, highlighting the need for simplified SSI methods. The impact of these simplifications on results is a crucial area of interest, as opinions differ on the best approach to model SSI accurately in practice.

3.1 Soil structure interaction

In civil engineering, structural elements like foundations, pavements, retaining structures, and tunnels often interact directly with the ground, creating what's known as soil-structure interaction (SSI). This interaction requires both the structure and the ground to deform together due to their physical contact. Historically, SSI was often neglected for simplicity, but advances in technology now make it easier to consider, although it can still be complex and time-consuming. SSI can be modeled using two main approaches: the structural approach, which uses simplified elements like springs and beams, and the continuum approach, which applies differential equations to simulate soil behavior. The Winkler model, a popular structural method, represents the subgrade with vertical springs, simplifying implementation but potentially oversimplifying soil behavior.

3.2 Loading Condition

Various types of loads and forces act on a retaining wall, and their calculation is essential for its design. These forces on the retaining wall depends on multiple factors which are discussed. There are various types of loads and forces acting on retaining wall, which are:

1. Lateral earth pressure
2. Surcharge loads
3. Axial loads
4. Wind on projecting stem
5. Impact forces
6. Seismic earth pressure
7. Seismic wall self-weight forces

Retaining wall design could include any or all of loads and forces which are explained in the following sections:

Lateral Earth Pressure Acting on Retaining Wall The main purpose of retaining wall construction is to retain soil; that is why soil lateral earth pressure is a major concern in the design. Sliding soil wedge theory is the basis for most of the theories by which lateral earth pressure is computed. The wedge theory suggests that a triangular wedge of soil would slide down if the retaining wall were removed suddenly, and the wall has to sustain this wedge soil. Figure shows free body lateral forces acting on retaining walls

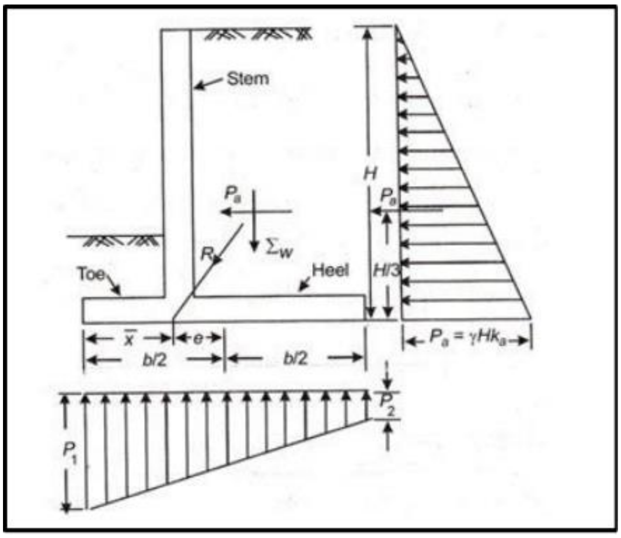


Fig 3.1 Forces acting on CRW

4. Research Methodology

In the steel industry, two primary methods for constructing industrial structures are Conventional Steel Buildings (CSB) and Pre-Engineered Buildings (PEB). CSBs use standard hot-rolled steel sections with varying designs, often incorporating concrete columns for support. They are versatile but can result in higher material wastage and lower construction precision due to bolted or welded connections. On the other hand, PEBs are designed and fabricated in factories to minimize material usage and streamline construction time. They are known for their efficient use of steel, quick assembly, and reliable performance under diverse conditions, supported by stringent design standards like IS 875 and IS 800 for load analysis and steel design, respectively. This comparison highlights PEBs' advantages in cost-effectiveness and rapid deployment, making them a preferred choice for many industrial applications seeking both efficiency and durability.

4.1 Flow of Research Work

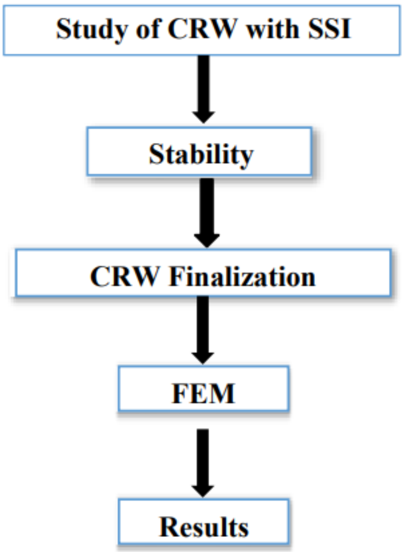


Fig 4.1 Flow chart of current Dissertation

4.2 Analysis of CRW using FEM with & without SSI

Finalized crosses section of CRW for various heights & profile are analyzed with & without soil mass using finite element package of ANSYS 18.0. While considering the soil mass various options & references are tried in which Swedish slip circle which is convenient for failure of embankment is adopted to finalize soil mass required for interaction. Embankment having factor of safety 1.5 is considered as per requirement of soil parameters. Failure surface as the part of Swedish slip circle are drawn along with cross section of CRW as shown in fig. 4.2

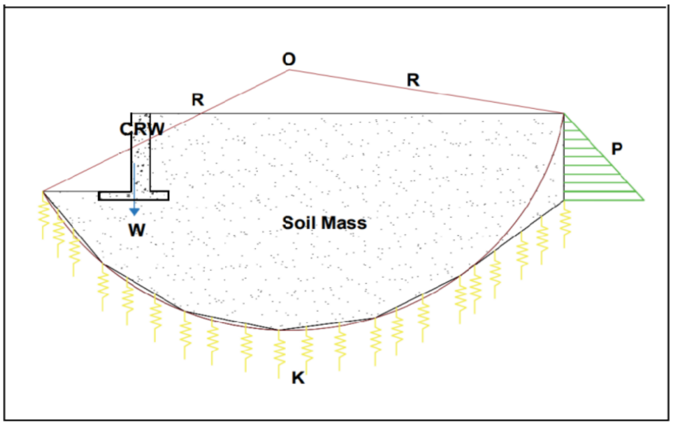


Fig 4.2 Swedish Slip Circle

Where,

W: Self Weight of CRW R: Radius of Slip Circle

O: Center of Slip Circle

P: Horizontal Pressure Applied on CRW with SSI consideration

K: Elastic Spring Constant

5. Results

The current project work is to study the effect of SSI on Cantilever retaining wall as per flow of project mentioned in the previous chapter. Profiles of cantilever retaining wall and parameters considered for the analysis of cantilever retaining wall with SSI as discussed in previous chapter. Cantilever retaining wall with different geometry and heights are designed governed by stability criteria dimensions of cantilever retaining wall for various Heights are calculated using worksheet. Which are separately developed for design of cantilever retaining wall with considering horizontal backfill as a loading case (details given as per appendix A). As per flow of proposed study two earthquake sample cases are considered. The various Heights with different geometry with and without consideration of soil structure interaction along with different earthquake cases are solved using finite element package of ANSYS. Maximum and minimum of the deformation and stresses obtained for each case, the non-dimensional variations are plotted and discussed in the current chapter.

5.1 Parameter Considered for Research Work

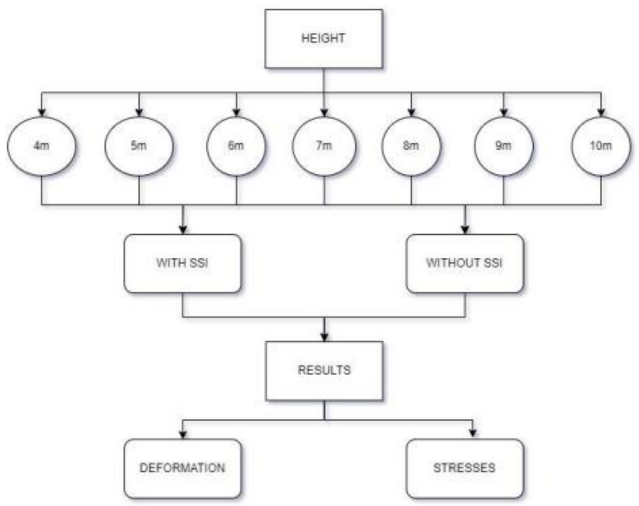
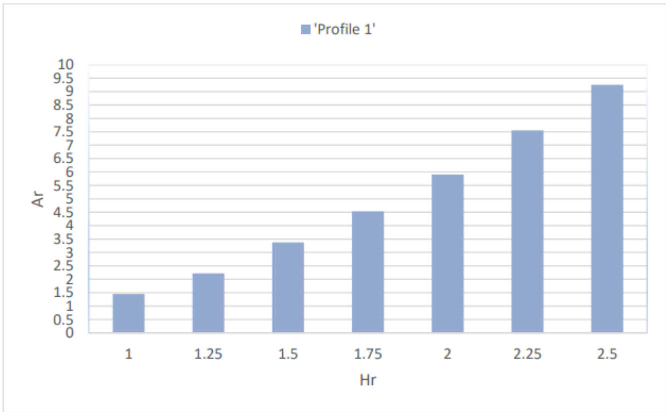


Fig 5.1 Flow Chart of the Dissertation

As mentioned in figure. 5.1 Various height of cantilever retaining wall are considered for analysis. For each case maximum deformation and maximum stresses (Tensile stresses) and minimum stresses (Compressive stresses) with and without soil structure interaction are obtained. The results obtained from the finite element analysis are tabulated in table number A.1, A.2, A.3 and A.4 etc. given in Appendix A.

5.2 Variation of cross-section area of CRW with Heights

As mentioned, worksheets are developed for design of cantilever retaining wall using stability criteria. It is observed that (appendix A) stability against sliding is governing stability criteria for design of cantilever retaining wall. Variation of cross-section area of CRW as per various Heights can be observed from the Plot G1 and for different profile two different terms are defined for the generalizing the results are as follows. Cantilever Training wall with 4 m height is considered as a reference case and the term are defined with reference of case considered. The height ratio (Hr) is defined as the ratio of height of cantilever retaining wall to the ratio of height of cantilever retaining wall considered as a reference case. Cross-section area ratio Ar is defined as Cross-section area of cantilever retaining wall to the Cross-section area of cantilever retaining wall of reference case



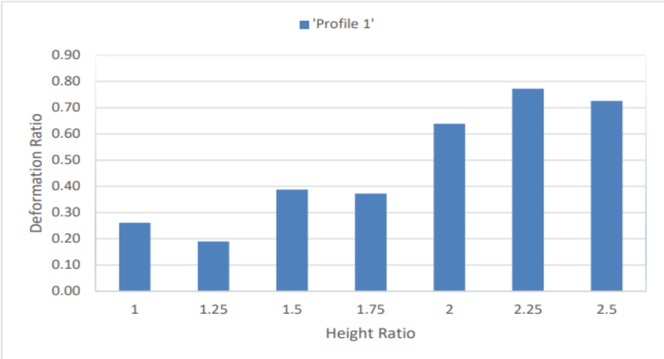
Graph G1: Variation of Area ratio (Ar) against Height ratio (Hr) of CRW

For Plot G1 shows that, the columns of chart are increasing in uniform order.

From plot G1 as the Hr increases Ar also increases simultaneously.

5.3 Variation of deformation percentage of CRW considering SSI with height ratio

The variation of the Deformation percentage of cantilever retaining walls with and without soil structure interaction are considered & plotted against Hr (As mentioned above) referring to table no.3 (Appendix A) The Deformations are obtained as per considered loading case, only retaining wall and retaining wall with soil mass (considering soil structure interaction). Are analyzed using FEM package as per cases mentioned in the fig.5.1.



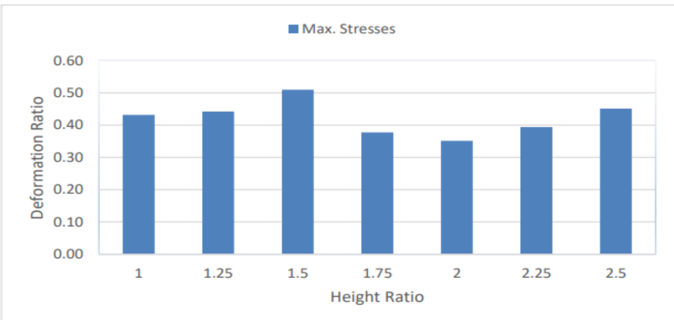
Graph G2: Variation to Deformation percentage of CRW with SSI considering against Height ratio (Hr)

Plot G2 shows that, all the two profile showing variations in deformation percentage compare with CRW without SSI. Considering only structure and with soil mass.

Following observations are noted, From above plot profile, showing variation of deformation percentage which is substantially reduced as compared to without SSI. The deformation percentage including all height is only 0.9 percentage as compared to without SSI (that is 99.1 percentage reduction is observed.) For Profile shows variation of deformation percentage increases up to maximum value that is 0.8 percentage. There after deformation percentage uniform up to Hr. 1.75. Afterwards the variation in Deformation percentage is abruptly increases. For Profile show Maximum deformation percentage at Hr 2.5.

5.4 Variation of maximum Stress percentage of CRW considering SSI with height ratio

The variation of the Maximum Stresses percentage of cantilever retaining with and without soil structure interaction are considered & plotted against Hr (as mentioned above) referring to table no. 4 (Appendix A) The Maximum Stresses are obtained as per considered various height case, only retaining wall and retaining wall with soil mass (considering soil structure interaction). Are analyzed using FEM package as per cases mentioned in the fig.5.1.



Graph G3: Variation to Maximum stress percentage of CRW with SSI considering against Height ratio (Hr)

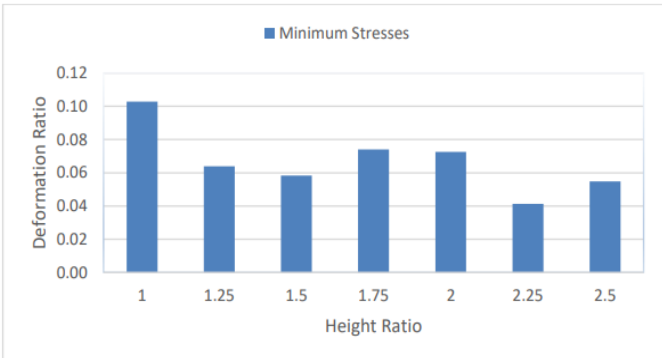
Plot G6 shows that, all the height showing variations in Maximum Stresses percentage compare with CRW without SSI. Considering only structure (excluding soil mass) and with soil mass.

Following observations are noted,

From above plot profile, showing variation of Maximum Stresses percentage which are substantially reduced as compared to without SSI. The maximum Stresses percentage including all profile is only 0.51percentage as compared to without SSI (that is 99.49 percentage reduction is observed.) 1. For Profile shows variation of Maximum Stresses percentage increases up to maximum value that is, 0.51percentage. There after Maximum stresses percentage decreases up to Hr 1.5. Afterwards the variation in maximum stresses percentages are not much significant.

5.5 Variation of minimum Stress percentage of CRW as per dynamic loading (Kobe) considering SSI with height ratio for different types

The variation of the minimum Stresses percentage of cantilever retaining wall as per dynamic loading (Kobe) with and without soil structure interaction are considered & plotted against Hr (as mentioned above) referring to table no. 8 (Appendix A) The minimum Stresses are obtained as per considered dynamic loading case, only retaining wall and retaining wall with soil mass (considering soil structure interaction). Are analyzed using FEM package as per cases mentioned in the fig.5.1.



Graph G4: Variation to Minimum stress percentage of CRW with SSI considering against Height ratio (Hr)

Plot G4 shows that, all profiles are showing variations in minimum Stresses percentage compare with CRW without SSI. Considering only structure (excluding soil mass) and with soil mass. Following observations are noted, From above plot profile, showing variation of minimum Stresses percentage which are substantially reduced as compared to without SSI. The variation of compressive stresses are practically not differ for all profile consider effect of SSI. The range of percentage stress remains in 0.04 to 0.1 % that itself indicate the wall without considering SSI having reserve strength which increases almost 99.09 with consideration of SSI. The variation shoes net change in profile does not affect minimum induce stresses.

5. CONCLUSIONS

The study on Soil-Structure Interaction (SSI) in Cantilever Retaining Walls (CRWs) reveals that including SSI in the analysis significantly impacts the structural performance of CRWs. The cross-sectional area of the walls increases substantially with height. When SSI is considered, deformation decreases markedly, showing a reduction of up to 0.9% for lower height ratios and approaching unreformed conditions at higher ratios. Maximum stresses are also reduced by up to 0.51%, and minimum stresses by 0.1%, with higher height ratios leading to negligible stress levels compared to models without SSI. Overall, the interaction between the soil mass and the retaining wall plays a crucial role in minimizing deformation and stress, enhancing the stability and efficiency of the structure across varying heights.

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