M.Tech (Geotechnical Engineering) Anurag Krishna Mishra (23/GTE/01) 2025

STABILITY ANALYSIS OF REINFORCED EARTH WALL UNDER STATIC AND DYNAMIC LOADING USING RS2

A dissertation submitted
In partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

IN

GEOTECHNICAL ENGINEERING

By

Anurag Krishna Mishra

(2K23/GTE/01)

Under the supervision of

Prof. Amit Kumar Shrivastava
Co-Supervisor
Prof. K .S .Rao

DEPARTMENT OF CIVIL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
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Shahbad, Daulatpur, Main Bawana Road, Delhi-110042, India

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CANDIDATE'S DECLARATION

I **Anurag Krishna Mishra (2K23/GTE/01)** student of M. Tech. Geotechnical Engineering, hereby certify that the Project dissertation titled "**Stability analysis of reinforced earth wall under static and dynamic loading using RS2"** In partial fulfillment of the requirements for the Degree of **Master of Technology (Geotechnical Engineering)**, Submitted in the Department of Civil Engineering, Delhi Technological Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from January 2025 to May 2025 under the supervision of **Prof. A.K. Shrivastava** and Co-supervisor **Prof. K. S. Rao.**

The content presented in the report has not been submitted for the award of any other degree of this or any other institute.

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and that the statement made by the candidate is correct to the best of my knowledge.

Anurag Krishna Mishra

Place: Delhi

Date: (Signature of Examiner)

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CERTIFICATE

It is certified that Anurag Krishna Mishra (2K23/GTE/01) has carried out their research work presented in this report entitled **"Stability analysis of reinforced earth wall under static and dynamic loading using RS2"** for the award of the degree of Master of Technology from the Department of Civil Engineering, Delhi Technological University, Delhi, under my supervision. The report embodies results of original work, and studies are carried out by the student himself and the contents of the report do not form the basis for the award of any other degree to the candidate or anybody else from this or any other University/Institution.

Place: Delhi

Date: 31/05/2025

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ABSTRACT

Mechanically stabilized earth (MSE) walls are widely employed in transportation infrastructure, where they are frequently subjected to both static and traffic-induced dynamic loads. This thesis presents a numerical investigation into the performance of a 6-meter-high geostrip-reinforced MSE wall under static and dynamic loading conditions using RS2 (Rocscience), a 2D finite element analysis (FEM) software. The study focuses on evaluating shear stress distribution and horizontal displacement while examining the effects of varying geostrip reinforcement lengths and the inclusion of filter media.

Dynamic loading is simulated based on vehicle-induced excitation, representing the transient stresses and vibrations typically encountered near roadways or embankments. Results show a progressive increase in shear stress from the wall crest to the base under both loading conditions. Under dynamic loading, localized stress peaks emerge, attributed to transient wave interactions within the reinforced soil zone, especially near the anchorage regions. Horizontal displacement is the most significant at the top of the wall, with dynamic loading producing displacements up to ~104.79 mm, in contrast to sub-10 mm displacements observed under static conditions.

Parametric analysis reveals that increasing reinforcement length from 0.3H to 0.7H effectively reduces both shear concentrations and lateral displacements. The incorporation of filter media—used for structural moderation rather than drainage—further enhances wall performance by facilitating better stress distribution and reducing deformation under traffic-induced dynamic loads.

This study highlights the need for dynamic-specific design strategies for MSE walls subjected to vehicular loading. It concludes that longer geostrip reinforcements combined with structural filter layers significantly improve wall stability, displacement control, and long-term performance in transportation-related applications.

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Last but not the least, I send my familiarization to family for all the overriding affection, care, and patience as well as their strength. Their expectations for me have been useful most of the time and at critical periods of this journey.

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CHAPTER 1

INTRODUCTION

Reinforced earth wall also known as MSE wall, commonly referred to as Reinforced Earth (RE) walls, are increasingly utilized in infrastructure development due to their structural efficiency, ease of construction, and adaptability to various site conditions. Compared to traditional gravity or cantilever retaining walls, RE walls offer several benefits, including lower construction costs, reduced material consumption, flexibility under differential settlement, and improved performance under heavy or dynamic loads.

These walls consist of precast concrete facing panels connected to horizontal reinforcing elements such as Para-web or Geostrips. These reinforcements are embedded within compacted backfill soil and are responsible for stabilizing the retained soil mass. Typically, the installation of both the reinforcement and facing elements occurs concurrently, streamlining the construction process. An essential factor in the long-term performance of RE walls is proper drainage. To prevent the accumulation of water and minimize hydrostatic pressure, a layer of filter media—ranging from 300 mm to 600 mm in thickness—is placed between the backfill and the facing panels. Although drainage design is crucial, this study does not account for the effects of water or pore pressure. Nevertheless, the filter and backfill materials must meet specifications provided by IRC-56 and MORTH, which require that the percentage of fine particles in the backfill soil remain below 15%.

The development of MSE wall systems began in 1971, with the first installation along State Route 39 in California. Since then, the technique has seen widespread global adoption, with tens of thousands of walls constructed across various terrains and applications. Some structures have reached heights of up to 30 meters, showcasing the capability of RE walls in supporting large-scale infrastructure. Despite their widespread use and advantages, the structural performance of RE walls depends heavily on reinforcement design and field execution. Insufficient reinforcement length or improper compaction can compromise wall stability, potentially leading to partial or complete failure. A well-known incident occurred in Turkey in 2021 (Fig 1.1), where such deficiencies led to a significant wall collapse.

This research aims to investigate the factors like influence of reinforcement length on the structural behaviour of RE walls under both static and dynamic conditions induced by vehicular movement. Using RS2 finite element software, the study evaluates the distribution of shear stress and horizontal displacement for different reinforcement configurations. It also considers the contribution of filter media in enhancing wall performance under dynamic loading. The findings from this investigation are expected to support improved design methodologies and contribute to the development of more robust and durable RE wall systems.

1.1.Problem Statement for Thesis

The design and analysis of geosynthetic-reinforced soil (GRS) structures rely heavily on numerical and physical modelling to predict critical parameters such as shear stress, horizontal displacement, and reinforcement efficacy under static and dynamic loading. However, significant discrepancies persist between numerical simulations (e.g., RS2 software) and physical model results, particularly when accounting for dynamic effects, filter media integration, and varying reinforcement configurations. Current methods, such as the earth pressure approach and K-stiffness method, often overestimate or underestimate reinforcement loads, while finite element analyses struggle with convergence under large soil strains. Furthermore, the interaction between reinforcement length, filter media, and impact energy (e.g., free-fall height and mass) remains poorly quantified, leading to suboptimal design guidelines for scenarios involving high-energy impacts or seismic activity.

1.2. Key Gaps Identified

1. Model Validation**:** Physical models (e.g., centrifuge tests) and numerical simulations (RS2) show inconsistent stress-displacement trends under dynamic conditions, especially at higher impact energies (e.g., 30 cm drop height vs. 10 cm).

2. Filter Media Effectiveness**:** While filter media reduces deflection by 30–50% in static and low-energy dynamic cases, its performance diminishes significantly under high-energy impacts, yet current design methods fail to incorporate this energy-dependent behaviour.

3. Reinforcement Configuration: The interplay between reinforcement length (e.g., 0.3H, 0.7H) and load distribution under dynamic loading is not systematically addressed, leading to conservative or unsafe designs.

4. Displacement-Stress Relationship: Horizontal displacements in physical models increase nonlinearly with structural height, but numerical models often under predict these values due to idealized boundary conditions and material properties.

1.3. Objective:

This thesis aims to bridge these gaps by conducting a rigorous comparative analysis of physical and numerical models for GRS structures under static and dynamic conditions.

This study will quantify the impact of the filter media, reinforcement length, and impact energy on shear stress redistribution and displacement. Develop calibrated numerical model in RS2 that account for dynamic soil-structure interaction and energy dissipation mechanics observed in physical tests. Propose revised design guidelines that integrate energy dependant filter media performance and optimize reinforcement configurations for seismic and impact resistant GRS structures.

By addressing these challenges, the research seeks to enhance the reliability of GRS design methodologies, ensuring safer and more cost –effective solution for infrastructure exposed to static and dynamic loads.

Figure 1.1 Turkey catastrophic RE Wall failure (2021) (AGU Blogsphere) [1]

RS2 (Rocscience 2D)

It is a powerful numerical modelling software widely used for geotechnical analysis. It allows simulation of both static and dynamic loading conditions using the finite element method (FEM). In this study, RS2 was used to model the behaviour of MSE walls under vehicle-induced impact loading.

The software supports complex soil-structure interaction, custom material definitions, time-dependent loading, and mesh refinement. For dynamic simulations, RS2 facilitates the use of time-history functions to model transient loads such as repeated axle impacts. The dynamic solver incorporates Rayleigh damping and allows the application of quiet boundaries to minimize wave reflection.

The MSE wall geometry, material properties, and reinforcement layout were modelled as per field and laboratory specifications. Equivalent static and dynamic axle loads, derived from the experimental study, were applied at the top boundary to simulate vehicle wheel impacts. Static analysis provided baseline behaviour, while dynamic analysis captured cumulative stress distribution, deformation, and wall rotation under transient loading.

In the numerical RS2 model simulating the full-scale wall, the reinforcement layout was replicated using 7 layers starting from 400 mm above the base, and spaced at 800 mm intervals, matching site conditions. By the help of this a more accurate representation of field behaviour compared to the scaled physical model, which used uniformly distributed reinforcement from the base upward. Differences in layout were acknowledged when correlating model and field results. And this process has been followed In the RS2.

- Geometry and boundary condition setup
- Static and dynamic mesh configuration
- Time-history load functions (single, tandem, tridem axle)
- Use of quiet boundaries and Rayleigh damping
- Simulation of physical model scenarios
- Variation with lab result

CHAPTER 2

LITERATURE REVIEW

Rahul Shende (2025) [2] highlighted deficiencies in Reinforced Earth (RE) wall design, identifying expansive clayey backfill as the principal cause of instability. Elevated earth and pore pressures due to high swelling and plasticity indices led to lateral bulging and compromised wall performance. Analyses under saturated and submerged conditions indicated design inadequacies, especially without proper drainage. Cohesionless backfill assumptions in soil nail calculations were deemed unsafe due to pull-out failures. Recommendations included accurate material characterization, effective drainage, and RCC wall construction with reinforced nailing for long-term stability.

Dhanya and Divya (2025) [3] conducted physical model tests to evaluate the hydro-mechanical performance of MSE walls backfilled with locally available marginal lateritic soils, which typically exceed the permissible fines content per IRC and MORTH guidelines. The study compared conventional geogrid (GG) reinforcement with composite geosynthetic reinforcements under construction, surcharge, and simulated rainfall conditions. Results indicated that while GG lost suction and experienced excessive deformation under rainfall, both CGRs performed significantly better in terms of strain control, facing deformation, and suction retention due to their enhanced drainage capabilities. Despite the marginal nature of the backfill, the use of composite reinforcements enabled acceptable performance under severe loading and environmental conditions. This demonstrates the viability of using locally available soils in MSE applications when reinforced with appropriately selected geosynthetics. The findings emphasize the importance of reinforcement type and drainage provisions in ensuring the stability of MSE walls, especially under varying moisture and load conditions.

Zhiyu Bai (2025) [4] implemented a Monte Carlo-based traffic simulation to model vehicle types, spacing, and speed, integrated with a dynamic analysis platform. Results showed structural response sensitivity to random heavy vehicle movement and increased vibration under high traffic density. Lane configuration influenced lateral displacements, suggesting central lane placement of heavy vehicles to mitigate effects. The study emphasized the importance of integrated modelling approaches for realistic load scenarios.

Susit Chaiprakaikeow (2024) [5] investigated the impact of wetting-drying cycles and soil-water retention curve (SWRC) hysteresis on stiffness behaviour in geosynthetic-reinforced soil (GRS) walls. Pore-water pressure distribution varied with depth, highlighting the role of drainage. Field observations diverged from lab data due to hysteresis, particularly at greater depths. The study emphasized integrated hydro-mechanical modelling for improved GRS wall design.

Venkata A. Sakleshpur (2024) [6] explored MSE wall performance, noting vertical stress increases from interface shear, downdrag, and inconsistent soil-reinforcement interaction. The study found reinforcement-panel connections underperformed relative to design expectations. It suggested using the critical-state friction angle for more reliable long-term design.

Shangchuan Yang (2024) [7] proposed a reduction factor (RFS) to assess working-state stability of GRS walls, enhancing traditional safety factor methods. Using active earth pressure theory, the model addressed soil–reinforcement interaction more accurately. RFS correlated with global stiffness, particularly with reinforcement length-to-height ratios exceeding 0.7, supporting realistic design predictions.

Apiniti Jotisankasa (2024) [8] monitored pore-water pressures in GRS walls, noting the highest values near the wall face, decreasing with depth due to underdrainage. Incorporating these profiles into design improved predictive accuracy. Minimal seasonal variation confirmed drainage effectiveness.

Bappaditya Manna (2024) [9] This study compared Terre Armée and RRR walls used in high-speed railway (HST) systems, highlighting that RRR walls, which use geosynthetic reinforcement and rigid facing, perform better in terms of deformation control. As a result, Japan discontinued the use of Terre Armée walls in HST projects due to deformation issues and corrosion risks. The study emphasized the importance of durable and low-maintenance designs for RER walls in HST applications, capable of withstanding extreme conditions without service interruption. It confirmed the viability of using cohesive or weathered materials when properly reinforced, as demonstrated in Japan's Nagano yard. Japan's RRR wall design also accounts for high seismic and rainfall loads, applying conservative safety measures. The preferred design approach is LRFD, which better handles load and material variability compared to ASD. The study also noted emerging trends in applying artificial intelligence and the use of metaheuristic algorithms to improve construction, monitoring, and design optimization of RE walls, presenting opportunities for future research.

Kaan Yünkül (2024) [10]emphasized the importance of reinforcement layer location, tensile stiffness, and backfill inclination angle in assessing shear behaviour of polymeric geostrip-reinforced MSE walls. Future research should consider varied soil types, reinforcement configurations, seismic loads, and narrow backfill conditions for comprehensive modelling.

Kianoosh Hatami (2024) [11] conducted pullout tests on geogrids in clay under varying moisture contents, assessing performance improvements using drainable granular layers. The study highlighted the benefits of marginal soil application and visualized reinforcement-soil interaction using PIV techniques.

Fei-fan Ren (2022) [12] conducted model tests on SMSE walls for embankment widening, revealing deformation in upper wall sections and bulging near top reinforcement. Horizontal earth pressures followed a K-distribution, with high pressures at the toe. The sandwich connection method was effective in controlling deformation and protecting existing structures.

Richard J. Bathurst (2021) [13] The study compares Terre Armée and RE wall systems used in high-speed railways, highlighting superior performance of RE walls in minimizing deformation. As a result, Japan phased out Terre Armée walls in such applications due to their susceptibility to corrosion and higher deformation under load. The study underscores the importance of resilient, low-maintenance RE wall designs capable of withstanding extreme environmental conditions without disrupting service. Field evidence supports the use of cohesive and weathered materials when properly reinforced, expanding the applicability of RE walls in varied contexts.

It also discusses the evolution of design practices, noting that Japan's railway systems adopt highly conservative methods to account for seismic and rainfall hazards. The use of limit state design (LRFD) is favoured over allowable stress design (ASD) for better handling of uncertainties in load and material behaviour. The study further emphasizes the growing role of artificial intelligence and the use of metaheuristic algorithms in optimizing RER wall design, construction, and monitoring—marking a progressive shift toward data-driven and adaptive infrastructure solutions.

Richard J. Bathurst (2021) [14] the study evaluated a steel strip-reinforced MSE wall using field instrumentation to monitor stresses, displacements, and reinforcement behaviour. It revealed that actual stress conditions differed from design expectations due to interface shear and construction-related effects. Tensile loads at the reinforcement-facing connections were lower than predicted, and design methods were sensitive to assumed soil friction angles. The findings supported the use of critical-state friction angle for more accurate and durable designs, emphasizing the importance of incorporating field conditions and construction influences into MSE wall analysis.

Hossain et al. (2012) [15] This case study analysed the excessive movement of a mechanically stabilized earth (MSE) wall constructed in Texas, attributing the deformation primarily to the use of backfill soil with high fine content and poor drainage characteristics. Field investigations and laboratory testing identified perched water zones and clayey sand backfill as key contributors to the wall's instability. The presence of water-induced pressures led to bulging of facing panels and overall wall movement. Numerical modelling validated the field observations and further highlighted the role of inadequate reinforcement length and drainage provisions. The study emphasized the importance of selecting appropriate backfill materials and reinforcement design, as well as ensuring effective drainage to maintain long-term wall stability.

CHAPTER 3
STUDY LOCATION

The project study is located along the ongoing four-laning of the Bhiwani to Hansi section of National Highway NH-148B. The specific site lies at the intersection of the Bhiwani–Rohtak Road and NH-148B, near Chainage 0+060. This location is situated close to the Bamla Toll Plaza in Bhiwani district, Haryana, India. The coordinates of the survey area are approximately **28.799499° N latitude and 76.188997° E longitude**. The figure below illustrates the exact position of the survey area as viewed in Google Earth.

The 4-laning of the Bhiwani-Hansi section of National Highway-148B under the Bharatmala Pariyojana in the Bhiwani and Hansi districts of Haryana. The project aims to enhance inter-district connectivity and ensure faster and more efficient movement of traffic within the state.

The development of this road section is expected to improve the overall efficiency of long-distance travel and freight transport. It will contribute to smoother and safer traffic flow, reduce travel time, and lower vehicle operating costs. Additionally, the project will strengthen the region's basic infrastructure and support broader economic development.

Figure 3.1 Site location of study

3.1. Description of the Field of Study and Material Properties

The study area involves the construction of a reinforced soil structure as part of the four-laning project on NH-148B. Sandy soil is used as the backfill material; however, due to its unavailability in the vicinity, it is borrowed from an external source. For drainage purposes, a filter media is used in conjunction with a geocomposite material.

Geostrip are employed as the primary reinforcement material, while precast concrete panels are used for the wall facing. To absorb shocks and reduce stress transfer between adjacent panels, EPDM pads are installed between them.

Construction is carried out in a layer-by-layer manner. The first layer of reinforcement is placed at a height of 40 cm from the base, with subsequent reinforcement layers spaced at a vertical interval of 80 cm. The horizontal spacing between the reinforcement strips ranges from 100 cm to 120 cm.

3.2. Construction of Reinforced Earth Wall Using Geostrip Reinforcement

Reinforced Earth (RE) walls are a type of mechanically stabilized earth (MSE) structure that utilizes reinforcing elements embedded within a soil mass to improve its strength and stability. Geostrip, a high-strength geosynthetic reinforcement made of polyester fibers encapsulated in polyethylene or polypropylene sheathing, is particularly suited for long-term reinforcement due to its resistance to chemical and biological degradation.

3.3. Site Preparation

Before construction begins, the site must be cleared of vegetation, organic matter, and any unsuitable material. The foundation level is excavated and levelled to the desired elevation. A drainage layer of granular material or a geocomposite or both is typically placed at the base to prevent water accumulation and ensure stability.(Fig 3.2)

Key steps:

a) Marking and excavation to design depth
b) Compaction of the foundation subgrade.
c) Placement of a levelling pad usually a lean concrete (PCC) strip of around 300mm width is provided on below the panel to provide support.

Figure 3.2 Levelling of OGL

.

3.3.1. Installation of Facing Elements

The facing of an RE wall used here are precast concrete panels, rather than modular blocks, or wrapped-around geosynthetics. For Geostrip-reinforced walls, PCC panels are commonly used due to its strength and ease of alignment. And at this site we have used the precast concrete panels. (Fig 3.3)

Figure 3.3 Erection of RE Panel

Procedure:

Facing panels are placed on the levelling pad with temporary struts or bracing to ensure vertical alignment.

Joints between panels are fitted with compressible material or filter fabric to accommodate movement and prevent soil loss.

3.3.2. Placement of Reinforcement (Geostrip)

Geostrip strips are installed in horizontal layers at designated vertical spacings (typically 0.6 m to 0.8 m) as per design requirement by the MORTH and IRC. The length of each strip is determined on the basis of the required reinforcement length (generally 70% to 100% of height of wall).We are going to discuss the importance of the length in our study with the impact loading.(Fig 3.4)

Figure 3.4 Geostrip Installation

Process:

Each layer of Geostrip is anchored to the facing panel through a connection embedded in the panel or via frictional clamping.

The reinforcement strips are unrolled to the full designed length into the compacted fill. And the Geostrip are pinned in the soil with the help of S-clamp and the J-hooks to prevent the slip. Care must be taken in the installation of the Geostrip such that it should not be twisted such that it causes the unnecessary stress in the reinforcement and at-least 1m of overlapping of the Geostrip should be provided.

Figure 3.5 Grading of Embankment

3.3.3. Backfilling and Compaction

Selected backfill material is placed in layers ranging from 200 mm to 300 mm in thickness and compacted to meet the required density, typically achieving 95% of the Modified Proctor Maximum Dry Density. To prevent shifting or deformation of the facing panels during compaction, plate compactors are employed near the wall face. The compaction process for the backfill and the filter media is carried out concurrently but with different equipment. For the filter media, a light compaction roller—commonly referred to as a baby roller is used to minimize vibrations and reduce the risk of disturbing the wall structure. In contrast, the backfill layers are compacted using a heavier vibratory roller to ensure adequate compaction across the reinforced zone. The backfill soil is dressed by grader. (Fig 3.5)

Notes:

The backfill should be free-draining granular soil with low fines content to reduce the risk of hydrostatic pressure build-up.

Care is taken to prevent damage to the Geostrip during placement and compaction.

Reinforcement should lie flat without folds or wrinkles.

3.3.4. Layer-by-Layer Construction

The construction of the wall progresses in sequential lifts. Initially, a layer of backfill is placed and compacted to the specified thickness. Once compacted, a layer of Geostrip reinforcement is laid out horizontally and securely anchored, typically to the facing elements. This process is then repeated—each new lift of backfill is placed over the previously installed reinforcement layer, followed by another layer of reinforcement, continuing until the wall reaches its full height. Throughout construction, the facing panels are carefully aligned both vertically and horizontally at each lift using alignment jigs or templates. Regular checks are conducted during each stage to ensure that construction tolerances are maintained and that the wall structure remains properly aligned.

3.3.5. Drainage Provisions

To ensure long-term structural integrity and mitigate the buildup of hydrostatic pressure, an effective drainage system is integrated into the reinforced earth wall design. A perforated drainage pipe, typically wrapped in geotextile, is installed at the base of the structure, positioned directly behind the facing panels to collect and convey infiltrated water away from the wall. Behind the facing, a drainage layer comprising either a geocomposite drainage board or a graded granular filter facilitates the downward flow of water toward the toe drain system.

To tackle the migration of fine particles from the backfill into the drainage zone, a non-woven geotextile filter fabric is used as a separator between the backfill and the drainage media. The filter media itself is a well-graded mix designed to ensure both permeability and structural stability. This mix typically includes a proportioned blend of 40 mm, 20 mm, and 10 mm angular aggregates, combined with quarry dust (stone fines) to improve the gradation prevention of the backfill mixing to the filter media. Such a mix adheres to the filter criteria ensuring compatibility with the adjacent backfill, promoting effective drainage while preventing clogging or internal erosion (piping) of fines.

3.3.6. Finishing and Top Treatment

After reaching the final height:

At the end the wall height is finished with a cap or coping. And friction wall and crash barrier is provided at the top of coping. (Fig 3.6)

Figure 3.6 Friction wall and crash barrier

Figure 3.7

Figure 3.7 (a) Shows the s-clamp which is involved in the coupling of the Geostrip (b) Shows the j hooks is pinned into the soil with the 150-180 mm rods (c) Shows

the sieve size involved in the sand replacement method test used for the FDD Test for backfill soil(d) Shows that baby roller, which is involved in the compaction of the filter media since vibro roller produces more energy so it is not used for the compaction of the filter media since it is near the wall so it will reduces the stability of the RE wall (e) Shows the vibro roller involved in the compaction of the the backfill soil (f) EPDM Pads are used to absorbs the shock during the placement of the RE panel (g) Shows the Geostrip it comes with varying strength and used accordingly (h) Shows the placement of the Geostrip it is recommended that the overlapping of the Geostrip should be more than the 1m (i) Shows the formwork used in the preparation of the RE panel (j) Shows the curing yard for the RE panel.

CHAPTER 4

METHODOLOGY

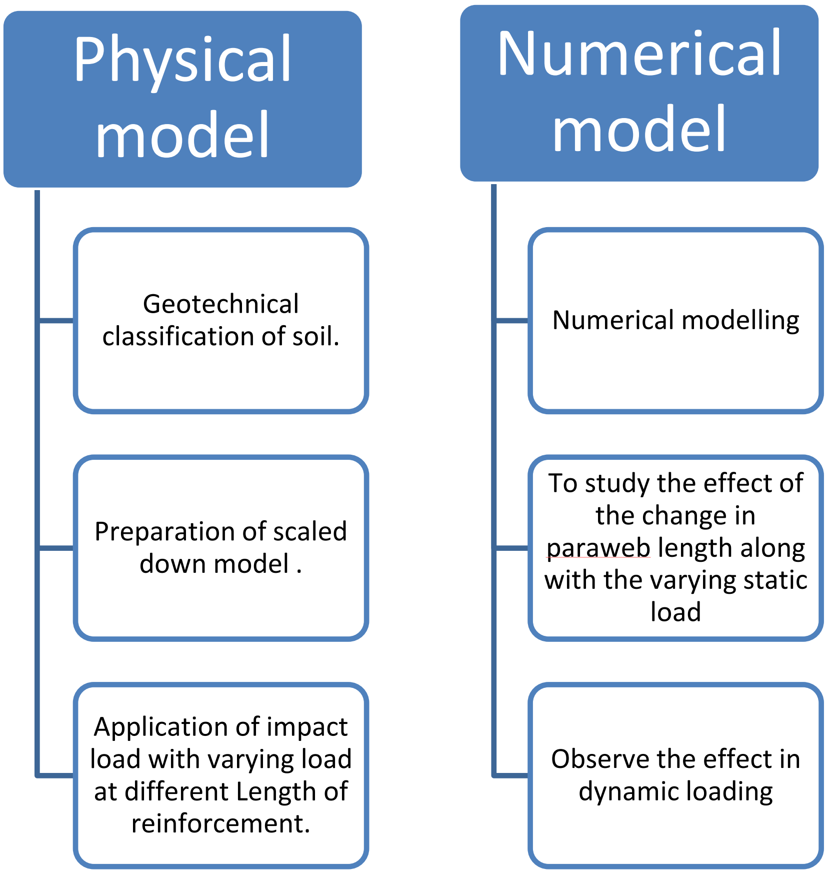

Figure 4.1 Flow chart of research

CHAPTER 4

PHYSICAL MODEL AND SOIL PROPERTY

Geotechnical Classification of Soil

4.1. Analysis of Particle Size Distribution

1.1 Introduction

It is the laboratory method for determining the particle size distribution of soils, particularly those containing fine particles like silt and clay. In this study, the backfill material used for the reinforced earth (RE) wall is a sandy soil with a notable presence of fine particles. To ensure accurate separation of these fines, the standard wet sieving method was adopted using a dispersing agent. This procedure helps in evaluating the suitability of the backfill material in terms of gradation, drainage potential, and reinforcement interaction.

1.2 Objective

The primary aim of this test is to accurately find the grain size distribution of the backfill sandy soil and to remove fine particles adhering to coarser grains. This is critical in reinforced soil structures, where fines can significantly affect drainage, compaction, and shear interaction with reinforcement materials.

1.3 Materials and Equipment

Air-dried soil sample (200 g), Sodium Hexametaphosphate (dispersing agent), 75 µm (No. 200), sieve, Set of standard sieves (4.75 mm to 75 µm),Balance (accurate to 0.01 g),Beaker (500 mL),Water spray bottle or wash bottle, Mechanical shaker, Oven (105°C to 110°C), Sieve pan and containers

1.4 Sample Preparation and Dispersion

A representative 200 g portion of the air-dried soil was taken. Since the soil included a fine fraction that could potentially cause flocculation, the sample was soaked in a 4% solution of **Sodium Hexametaphosphate ($Na_6P_6O_{18}$)** to aid dispersion. The dispersing solution was prepared by dissolving approximately 40 g of the compound in 1 liter of distilled solution of water. About 100 mL of this solution was mixed to the soil sample, and the mixture was allowed to soak for 12 hours to ensure complete dispersion of the fines.

1.5 Wet Sieving Procedure

After soaking, the soil-dispersant mixture was gently agitated for 5 minutes to ensure disaggregation. The mixture was then poured through a 75 µm (No. 200) sieve, placed over a basin. The retained material was washed using a gentle stream of water until the effluent appeared clear, indicating that most of the finer particles had been removed.

The material which was retained on the sieve was then transferred on a drying pan and oven-dried at 105°C for a minimum time of 24 hours. When the sample was cooled and subjected to dry sieving using a standard stack of sieves was arranged in descending order of mesh size. The stack was placed in a mechanical sieve shaker for 10–15 time of minutes to ensure proper separation of the remaining particles.

1.6 Calculation and Plotting

The weight of soil retained on each sieve was recorded, and the percentage passing was calculated using the following formula:

$$\boldsymbol{Percent\ finer} = \frac{\boldsymbol{Total\ weight - Cumulative\ retained\ weight}}{\boldsymbol{Total\ weight}} \times \mathbf{100} \tag{1}$$

A grain size distribution curve was then plotted on a semi-logarithmic graph with the particle size on the logarithmic X-axis and the percentage finer on the Y-axis. From this curve, key gradation parameters such asD_{10},D_{30} , D_{60}, coefficient of uniformity (Cu), and coefficient of curvature (Cc) were determined.

1.7 Importance in RE Wall Applications

In reinforced earth walls, the gradation of backfill soil plays a crucial role in determining the wall's stability and performance. The presence of excessive fines can hinder proper drainage, lead to pore water pressure build-up, and reduce friction between the reinforcement and soil. Wet sieve analysis ensures accurate quantification of the fines content, which is critical for:

- Ensuring adequate drainage behind the wall
- Avoiding excess pore pressure that could lead to structural instability
- Improving interaction between soil and reinforcement (e.g., geogrids, strips)
- Complying with specification limits, typically requiring <15% fines (passing 75 µm) for sandy backfill in RE walls

By dispersing and removing the fines prior to gradation analysis, the wet sieving process provides a more reliable assessment of the backfill material's suitability for long-term performance in RE wall systems.

Figure 4.1 Sample For Wet Sieving

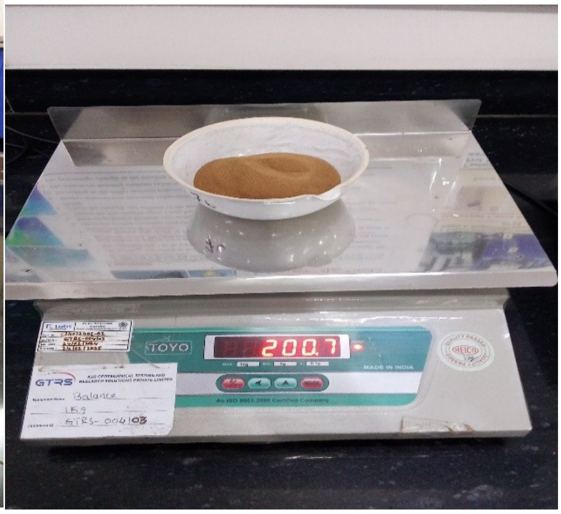

Figure 4.2 Solution used for Wet Sieving

These are derived from the sieve analysis curve (grain size distribution curve).

Key Grain Sizes:

- D10: Particle diameter at 10% finer (effective size)
- D30: Particle diameter at 30% finer
- D60: Particle diameter at 60% finer

Coefficient of Uniformity (Cu):

$$Cu = \frac{(D_{60})}{(D_{10})} \quad (2)$$

Coefficient of Curvature (Cc):

$$Cc = \frac{(D_{30})}{(D_{10}.D_{60})}$$

(3)

Typical Soil Classification Using Cu and Cc

- Well-graded gravel: Cu > 4, 1< Cc < 3
- Well-graded sand: Cu > 6,1< Cc <3
- Poorly graded soil: Does not meet the above criteria.

4.1.2 Density bottle method for Specific Gravity

As per IS 2720 (Part 3, Section 1):1980 – "Methods of Test for Soils: Determination of Specific Gravity"

2.1 Introduction

Specific gravity is defined as the ratio of the weight of a given volume of soil solids to the weight of equal's volume of water at a defined temperature. It is a fundamental physical property used in various geotechnical calculations, including void ratio, porosity, and degree of saturation. Accurate determination of specific gravity is particularly important for the design and analysis of backfill material in Reinforced Earth (RE) wall systems, where soil mass-volume relationships govern compaction and stability behaviour.

For sandy soils, which are free-draining and non-cohesive, the density bottle method provides an accurate and practical approach for determining specific gravity.

2.2 Objective

The purpose of this test is to find the specific gravity **(G)** of sandy backfill soil using the density bottle method, as described in IS 2720 (Part 3, Section 1):1980. The value obtained is used in subsequent compaction, permeability, and strength analyses of the RE wall backfill.

2.3 Equipment and Materials

Density bottle (50 mL capacity, with stopper), Oven (temperature: 105–110°C), Analytical balance (accuracy: 0.001 g), Funnel, Distilled water, Glass rod, Soil sample (oven-dried, passing 2 mm IS sieve), Desiccator.

2.4. Test Procedure

2.4.1 Soil Preparation

The soil sample was air-dried and then oven-dried at 105–110°C for a time period of 24 hours to remove moisture. It was then cooled in a desiccator and passing by a 2 mm IS sieve to remove coarse particles.

2.4.2 Weight of empty bottle (W_1):

The clean and dry density bottle, along with its stopper, was weighed using an analytical balance.

2.4.3 Weight of bottle + dry soil (W_2):

About **5–10 grams** of dry soil was added to the bottle, and the total weight was recorded.

2.4.4 Filling with water and removing air:

Distilled water was added to the bottle up to three-quarters full. The bottle was gently stirred with a glass rod to remove air bubbles. It was then completely filled with water and the stopper inserted. The bottle was allowed to stand until it reached room temperature.

2.4.5 Weight of bottle + soil + water (W_3):

The bottle containing soil and water was weighed.

2.4.6 Weight of bottle + water only (W_4):

The bottle was emptied, cleaned, and refilled with distilled water only, then weighed again.

Figure 4.3 Density Bottle

2.5 Calculations

The formula used to find the specific gravity is-

$$G = \frac{(W2 - W1)}{(W2 - W1) - (W3 - W4)} \quad \textbf{(4)}$$

The result is typically reported to two decimal places and, for sandy soils, should lie in the range of 2.60–2.70.

2.6 Importance in RE Wall Applications

Specific gravity plays a significant role in geotechnical design parameters relevant to RE wall systems:

a. Compaction Control

The specific gravity of soil solids is used in calculating maximum dry density and void ratio, which are key to ensuring proper compaction of backfill material.

b. Volume–Mass Relationships

Accurate G values allow for precise estimation of unit weight, porosity, and degree of saturation, all of which affect the wall's performance and stability.

c. Material Consistency

Specific gravity is also used to detect contamination or compositional changes in backfill material, ensuring consistency during construction.

d. Shear Strength & Permeability

Variations in G affect particle arrangement and thus influence strength and hydraulic conductivity of sandy backfills.

Conclusion

The density bottle method, as described in IS 2720 (Part 3, Section 1):1980, provides an accurate determination of the specific gravity of sandy soils used as backfill in RE wall systems. The measured G value confirms the quality and suitability of the soil for use in mechanically stabilized structures. This parameter is essential for ensuring reliable design, efficient compaction, and long-term performance of the RE wall.

4.1.3 Modified Proctor Compaction Test (As per IS: 2720 Part 8 – 1983)

3.1 Introduction

Compaction is a fundamental process in geotechnical engineering that improves the strength, stability, and durability of soil used in construction. The Modified Proctor Test, is employed to determine the maximum dry density and optimum moisture content of soil under high compactive effort. This is particularly relevant for backfill materials in Reinforced Earth (RE) wall systems, where the backfill must exhibit sufficient shear strength, low compressibility, and effective reinforcement interaction.

3.2 Objective

The primary objective of the Modified Proctor Test is to establish the relationship between the moisture content and the dry density of a given soil when subjected to a higher compactive effort than the Standard Proctor Test. The resulting parameters—maximum dry density (MDD) and optimum moisture content (OMC)—are essential for specifying field compaction targets to ensure the stability and performance of RE walls.

3.3 Equipment and Materials

Compaction mould (volume: 1/30 ft^3 or 944 cm^3), Rammer (mass: 4.54 kg drop height: 457 mm), Soil sample (approximately 3–5 kg of air-dried soil), Balance (accurate to 1 g), Oven (105°C to 110°C), Straight edge and spatula, Mixing tray and water

3.4 Test Procedure

3.4.1 Soil Preparation

A representative air-dried soil sample was passed through a 4.75 mm sieve to remove any oversized particles. The sample was divided into several portions and mixed with increasing amounts of water to prepare specimens at different moisture contents—typically in the range of 6% to 16% for sandy soils.

3.4.2 Compaction Method

For each moisture content, the soil was compacted in a cylindrical mould in five equal layers, with each layer receiving 25 blows from a 10 lb rammer dropped from a height of 18 inches. This process ensures a total compactive energy of approximately 2,700 kN·m/m³ which is nearly 4.5 times greater than the energy used in the Standard Proctor Test.

After compaction, the collar was removed, and the surface was levelled with a straight edge. The compacted sample was then weighed, and a small portion of the soil was taken for moisture content determination.

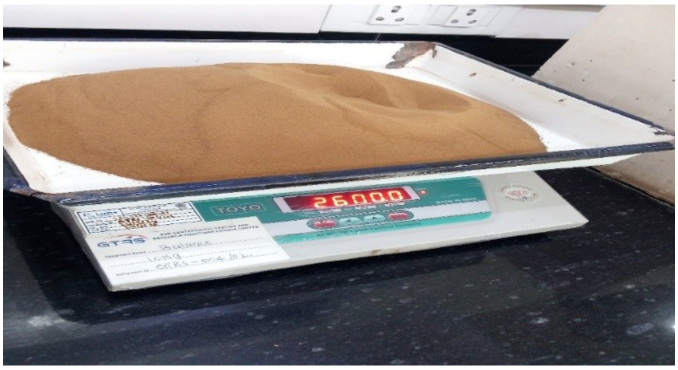

Figure 4.4 Sample used for compaction

3.5 Calculations

The **bulk (wet) density** was calculated using:

Dry density (ρd) formula

$$\rho d = \frac{\rho}{1 + \frac{w}{100}} \tag{5}$$

Compactive effort formula (Modified Proctor):

$$E = \frac{(N.n.W.H)}{V} \tag{6}$$

This process was repeated for each moisture content, and a dry density vs. moisture content curve was plotted.

3.6 Results and Analysis

From the plotted curve, the maximum dry density (MDD) and the respective optimum moisture content (OMC) were identified. These values are critical for field compaction operations, where soil must be compacted to at least 95% to 98% of MDD to meet structural and stability requirements for RE wall construction.

Importance in RE Wall Applications

The Modified Proctor Test is particularly significant in RE wall design and construction due to the following reasons:

a. Structural Stability

Backfill compacted to the proper density minimizes settlement and lateral deformation, enhancing wall stability and performance under static and dynamic loads.

b. Shear Strength Improvement

Compaction increases the shear strength of sandy backfill, which is vital for mobilizing sufficient frictional resistance between the soil and reinforcement (e.g., geogrids or strips).

c. Reinforcement Performance

Achieving MDD ensures optimal interaction between the reinforcement layers and the compacted soil, reducing the risk of slippage or excessive strain under load.

d. Drainage and Durability

Proper compaction reduces voids and permeability variability, helping maintain consistent drainage and preventing water accumulation behind the wall.

e. Quality Control

Field compaction is verified against laboratory-obtained MDD and OMC values. Therefore, the accuracy of this test directly impacts construction quality assurance.

4.1.4 Direct Shear Test for Sandy Backfill in RE Wall Construction

As per IS 2720 (Part 13):1986 – "Methods of Test for Soils: Direct Shear Test"

4.1 Introduction

The Direct Shear Test it is a widely used method in geotechnical engineering for find the shear strength parameters of soil specifically, the cohesion (c) and angle of internal friction (φ). These parameters are crucial for designing Reinforced Earth (RE) **walls**, as they define the shear resistance offered by the backfill material. In sandy soils, which are primarily cohesionless, the friction angle becomes the governing factor in assessing stability and interaction with reinforcement elements.

This test was conducted in accordance with the Indian Standard IS 2720 (Part 13):1986, which outlines the procedure for direct shear testing of soils under drained conditions.

4.2 Objective

The objective of the test is to determine the shear strength characteristics of sandy backfill soil by applying controlled normal loads and measuring the corresponding shear force required to cause failure. The resulting shear strength envelope is used in the design and stability analysis of RE wall systems.

4.3 Equipment and Materials

Direct Shear Test apparatus (as per IS 2720 Part 13),Shear box assembly (60 mm × 60 mm × 25 mm),Loading frame with proving ring or load cell, Dial gauges (for horizontal and vertical displacement),Weights for applying normal load, Soil sample (air-dried, sandy soil),Balance (accuracy of 0.01 g),Tamper, spatula, and container, Stopwatch

4.4 Test Procedure

4.4.1 Sample Preparation

The air-dried sandy soil was passed through a 4.75 mm IS sieve and filled into the shear **box** in three equal layers, each compacted gently to achieve a uniform and representative density. The top surface was levelled, and the sample height was maintained at approximately 25 mm.

4.4.2 Application of Normal Load

A normal stress (e.g., 50, 100, and 150 kPa) which is converted by the 10X application of 0.5kg,1kg,1.5kg was applied on the soil sample through a vertical loading mechanism. The load was applied incrementally and maintained constant during the entire shearing process.

4.4.3 Shearing Operation

The lower half of the shear box was moved horizontally at a constant strain rate of 1.25 mm/min, as recommended for sandy soils. The applied horizontal force and corresponding displacement were measured using a proving ring and dial gauge, respectively.

The shearing was continued until the peak shear load was reached or until large displacements occurred, indicating failure. The test was repeated under at least three different normal stresses to construct the Mohr-Coulomb failure envelope.

Figure 4.5 Sample for DST

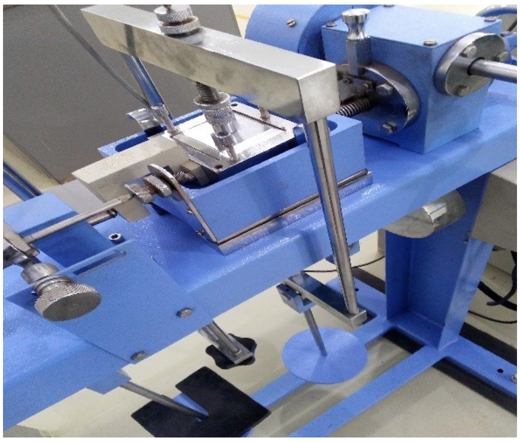

Fig 4.6 DST Apparatus

4.5 Calculations

The shear stress (τ) and normal stress (σ) were computed as:

$$\tau = \frac{F}{A} \quad (7)$$

$$\sigma = \frac{N}{A} \tag{8}$$

The corrected area is used for the reduction in contact area during shearing:

$$A = A_0 - \delta h \tag{9}$$

From the plot of shear stress vs. normal stress, and the Mohr-Coulomb failure envelope was developed. The slope of the line gives the angle of internal friction (φ), and the intercept on the shear stress axis gives the cohesion (c):

$$\tau = C + \sigma \tan \varphi \tag{10}$$

Importance in RE Wall Applications

The Direct Shear Test provides essential data for designing and assessing the performance of RE walls:

a. Soil–Reinforcement Interface

A higher (φ) value improves pull-out resistance and bond strength between soil and reinforcement (e.g., strips or geogrids).

b. Internal Stability

The shear strength parameters help assess the potential for internal failure within the reinforced zone.

c. Drainage Considerations

Sandy soils with low cohesion and high permeability are ideal for RE wall backfills, minimizing pore pressure development.

d. Material Specification

Many standards (e.g., MORTH, FHWA) recommend backfill materials with $\varphi \geq 30°$, which this soil satisfies.

4.1.5 Gradation Test For filter

Filter Media Evaluation for Backfill Drainage in Reinforced Earth Walls

As per IS 1498:1970, IS 8408:1994, and FHWA-NHI-07-092

5.1 Introduction

In Reinforced Earth (RE) wall systems, efficient drainage behind the wall is essential to avoid hydrostatic pressure build-up and loss of strength in the backfill material. A filter layer is placed between the reinforced soil and the drainage layer to ensure water passes freely while retaining soil particles. This is particularly important when non-cohesive sandy **soils** are used as backfill.

The suitability of the filter material is evaluated by sieve analysis and compared against standard filter criteria, which ensure the prevention of soil piping and adequate permeability.

The sieve analysis was done to determine the particle size distribution of the filter media used behind the reinforced earth (RE) wall. A well-graded filter material is essential to allow free drainage while preventing the migration of fine soil particles from the backfill. The test followed a systematic process as detailed below:

1. Sample Collection and Preparation

A representative sample of approximately **29.33 kg** was collected from the stockpile of the filter material. The sample was visually inspected for moisture content. If any noticeable moisture was present, the entire sample was placed in an oven and dried at a temperature of **105°C to 110°C** until a constant weight was achieved. This ensured accurate weight measurements and effective particle separation during sieving.

2. Selection and Arrangement of Sieves

A set of standards IS **sieves** was selected, covering a range from **26.5 mm to 0.09 mm**, arranged in descending order of opening size. A sieve pan was placed at the bottom to collect the finest particles. All sieves were cleaned before use to prevent contamination or blockage that could affect results.

3. Weighing of the Dry Sample

Once dried, the entire soil sample was weighed using a digital weighing balance. The initial weight was recorded accurately, as it would be used for calculating the percentage retained and passing for each sieve.

4. Sieving Process

The dried sample was carefully poured into the top sieve of the stack. The sieve stack was then placed into a mechanical sieve shaker and operated for about **10 to 15 minutes** to allow sufficient time for the particles to separate based on size. After mechanical shaking, the stack was disassembled, and each sieve was manually tapped and brushed to collect any particles that might not have passed during shaking.

5. Weighing of Retained Material

The material retained on each sieve was carefully transferred into separate containers and weighed individually. These values were recorded and used to calculate the cumulative weights and percentages for analysis.

2. Objective

To assess whether the selected filter media satisfies the gradation-based criteria to: Prevent loss of fine particles from backfill, Allow adequate drainage, Avoid clogging and ensure long-term performance of the RE wall

3. Standards Followed

IS 1498:1970 – Classification of soils

IS 8408:1994 – Guidelines for underdrain systems with gravel filter media

FHWA-NHI-07-092 – Design manual for mechanically stabilized earth walls

4. Sieve Analysis of Filter Media

4.1 Test Setup

A dry sieve analysis was conducted using a stack of IS sieves and a mechanical sieve shaker. The results are tabulated below:

Note: Total sample weight = 29,173 g

the material is well-graded and falls within **MORTH Class 2 filter material** limits.

5. Filter Criteria Evaluation

To determine the effectiveness of the filter material for RE wall backfill, the following criteria are applied:

Figure 4.7 Sample Used for Filter media test

Fig 4.8 Sieve Size

5.1 Retention Criterion *(To prevent soil piping)*

$$\mathbf{D_{15(filter)} \leq 4 \times D_{15(soil)}}$$

Assume from Backfill sieve analysis:

$$D_{85(soil)} = 0.35mm$$

From graph or distribution table:

$$D_{15(Filter)} \approx 0.65mm$$

$$0.65 \leq 4 \times 0.35 = 1.4$$

Permeability Criterion (To Ensure drainage)

$$D_{15(filter)} \geq 4 \times D_{15(Soil)}$$

Assume from soil analysis:

$$D_{15(soil)} = 0.12mm$$

$$0.65 \geq 4 \times 0.12 = 0.48$$

Uniformity coefficient of filter (Cu)

$$C_U = \frac{D_{60}}{D_{10}}$$

$$D_{60} = 2.5mm , D_{10} = 0.2mm$$

$$C_u = \frac{2.5}{0.2} = 12.5$$

Cu < 20

6. Interpretation of Results

The filter material:

- Meets MORTH Class 2 requirements.
- Satisfies filter design criteria for drainage and soil retention.
- Has a well-graded distribution, ensuring minimal risk of segregation or clogging.

Importance in RE Wall Drainage

- Prevents build-up of pore pressure by facilitating quick removal of infiltrated water
- Avoids migration of fine particles from backfill, preserving wall integrity
- Reduces long-term maintenance and failure risk
- Ensures structural and hydraulic compatibility with reinforced fill

Conclusion

Based on sieve analysis and filter criteria, the selected filter media is suitable for use in RE wall backfill drainage systems. It complies with IR56 and MORTH guidelines, ensuring safe, effective drainage while maintaining particle retention and structural integrity.

4.2. Methodology for Physical Model Testing of RE Wall

This section outlines the approach used to construct and analyse a scaled physical model of a Reinforced Earth (RE) wall subjected to dynamic loading. The model was developed to replicate the actual site condition (NH-148B, Ch. 0+060 LHS) at a scale of 1:20, focusing purely on mechanical stability without the influence of water or seepage effects.

2.1 Model Scaling and Construction

The prototype RE wall at the site is 6 meters in height and 22 meters in width. For laboratory testing, a 1:20 scaled model was constructed using a test box of dimensions:

- Wall Zone: 30 cm (height) × 30 cm (length) × 30 cm (width)
- Observation Zone: 15 cm (glass panel side)
- Materials: HDMR plywood for the wall facing and glass panels for side observation

The model was filled in layers. A 5 cm base layer of compacted soil was placed for bedding. The RE wall facing was made using HDMR plyboard (30 × 35 × 0.5 cm), and the Geostrip reinforcement (tensile strength = 100 kPa) was embedded in it at three vertical levels: 9 cm, 18 cm, and 27 cm from the model's base, maintaining a vertical spacing of 5 cm.

2.2 Reinforcement Trials and Filter Media

To analyse the influence of reinforcement length and backfill composition on stability, the following four trials were conducted:

In Trial 4, a well-graded filter media was added behind the RE wall, scaled down proportionally from the site conditions (30% 20 mm aggregate, 23% 10 mm aggregate, 27% stone dust). While water movement is not simulated, the mechanical interlock and packing characteristics of the graded filter media were studied in terms of their effect on wall stability and reinforcement behaviour.

Table 1 Trial detail

Trial	Reinforcement length	Filter media use	Remark
Trial 1	0.3H (9cm)	No	Baseline model
Trial 2	0.5H(15cm)	No	Medium anchorage
Trial 3	0.7H(21cm)	No	Extended reinforcement
Trail 4	0.7H(21cm)	Yes(scaled down)	Site representative filter mix

2.3 Soil Compaction

All soil layers were compacted to achieve the Maximum Dry Density (MDD) at the Optimum Moisture Content (OMC), ensuring uniformity across all trials:

- OMC: 11.517%
- MDD: 1.847 g/cm³

Compaction energy was controlled to replicate the Modified Proctor effort. Each layer was placed in uniform thickness and compacted using a manual rammer to match field conditions at scale.

2.4 Impact Loading Conditions

Simulated dynamic loads were applied after completing wall construction in each trial to study the RE wall's resistance to localized impact. The same loading conditions were used for all four trials:

Masses: 2.5 kg, 3.5 kg, and 8.38 kg

Drop Heights: 15 cm (all masses) and 30 cm (8.38 kg only)

Repetitions: 5 impacts per loading case

Impact was delivered at the centre of the wall, minimizing boundary effects. The contact area was small to replicate a point load scenario, such as vehicular impact or falling debris.

Impact energy was calculated using:

$$\boldsymbol{E = m.g.h} \quad \textbf{(11)}$$

Impact force consuming constant stopping distance (S=0.01m)

$$F = (E/S) = (mgh/S) \tag{12}$$

Prototype Force Scaling $\lambda = 1/20$

$$Fp = F_m.(1/\lambda^2) \tag{13}$$

$$= F_m.400$$

Axle Load equivalent (2 wheels)

Axle Load=2.Fp

Calculation for each load case

Case 1- 2.5kg from 10cm (7drop)

E=2.5x9.81x0.1

E=2.4525J

$$F = (2.4525/0.01)$$

=245.25N

As per Scaling Law 245.25x400

= 98.1 kN

Axle Load Single drop =2x98.1

= 196.2 kN

& for cumulative =196.2x7

= 1373.4 kN

Case 2- Same procedure followed for 3.5kg drop from 10cm (7 drop)

Axle load for two wheels =274.68kN

Cumulative =1922.76kN

Case 3- 8.38kg Free fall from 10cm (5 drop)

Two-wheel axle load =328.83x2

=657.66kN

Cumulative load 5x657=3288.3kN

Case 4- 8.38kg Free fall from 30cm (5drop)

Two-wheel axle load =2x986.49 kN

Cumulative = 5x1972

=9867.9 kN

As per IRC:58-2015, the legal axle load limits in India are **100 kN for a single axle**, **186 kN for a tandem axle**, and **235 kN for a tridem axle**. However, it is widely observed that a significant number of commercial vehicles operating on national highways routinely carry axle loads that exceed these prescribed limits. In this study, efforts were made to select loading conditions that approximate or slightly exceed the IRC-specified values to realistically represent the overstressed conditions commonly encountered in the field. This approach provides a more practical basis for assessing the structural performance and resilience of MSE walls under actual traffic-induced loading scenarios.

2.5 Boundary Effects and Observations

To limit boundary interference and ensure accurate monitoring:

- Glass sidewalls were used for visual analysis
- Impact load was applied centrally
- Deformation and failure patterns were recorded visually

Observed parameters included:

- Wall deflection or tilting
- Soil bulging
- Reinforcement displacement or pull-out

- Settlement patterns after multiple impacts

2.6 Performance Evaluation

By comparing the four trials, the study assessed:

- The relationship between reinforcement length and stability
- The mechanical role of filter media (without water) in supporting the backfill and reinforcement
- The deformation response of the RE wall to increasing impact energy

It was observed that models with longer reinforcement (0.7H) showed reduced deformation and better energy absorption. The inclusion of graded filter media (Trial 4) further improved stability by enhancing soil structure and preventing localized bulging.

2.7 Summary

This experimental methodology replicates field conditions in a controlled lab environment using a scaled model. The influence of reinforcement length and filter media gradation was examined under dynamic loading, providing insights for optimizing RE wall design under mechanical loading conditions without water infiltration.

CHAPTER 4 (B)
NUMERICAL MODELLING IN RS2

To simulate and analyse the behaviour of the Reinforced Earth (RE) wall under real-world conditions, numerical modelling was carried out using RS2 (Rocscience software). The model was constructed to represent actual site conditions with full-scale dimensions, incorporating both static and dynamic loading scenarios.

Table 2 General settings used in RS2

Number of Stages:	4
Analysis Type:	Plane Strain
Solver Type:	Gaussian Elimination
Units:	Metric, stress as kPa
Permeability Units:	meters/second
Time Units:	Seconds

4.1 Model Geometry and Boundary Setup

The RE wall modelled in RS2 had a height of 6 meters and a width of 12 meters, closely reflecting the geometry observed at the site **(LHS of NH-148B at Ch. 0+060).** A foundation layer of dimensions 30 m × 8 m was first established at the base of the model, filled with soil having a higher density than the backfill material to represent stable subgrade conditions.

4.2 Material Properties and Reinforcement Layout

Material properties were assigned to different zones of the model, including the foundation soil, backfill soil, RE wall facing, and reinforcing layers. Reinforcement was incorporated in a layered pattern, beginning at a height of 40 cm from the base and spaced vertically at 80 cm intervals. Each reinforcing strip was modelled with its respective tensile strength and stiffness parameters. Liners were applied along each reinforcement layer in the vertical section to simulate interaction between soil and reinforcement.

Table 3 Properties of Backfill soil used in RS2 Model

Material Colour		
Initial Element Loading	Field Stress and Body Force	
Account for Moisture Content in Unit Weight	No	
Unit Weight	17.81 kN/m3	
Porosity Value	0.32	
Elastic Type	Isotropic	
Poisson's Ratio	0.3	
Young's Modulus	20000 kPa	
Failure Criterion	Mohr-Coulomb	
Material Type	Elastic	
Peak Tensile Strength	0 kPa	
Peak Friction Angle	34 degrees	
Peak Cohesion	0 kPa	
Material Behaviour	Drained	
Fluid Bulk Modulus	2.2e+06 kPa	
Static Water Mode	Dry	

Table 4 Properties of filter media used in RS 2 model

Material Color		
Initial Element Loading	Field Stress and Body Force	
Account for Moisture Content in Unit Weight	No	
Unit Weight	19.5 kN/m3	
Porosity Value	0.5	
Elastic Type	Isotropic	
Poisson's Ratio	0.3	

Young's Modulus	20000 kPa
Failure Criterion	Mohr-Coulomb
Material Type	Elastic
Peak Tensile Strength	0 kPa
Peak Friction Angle	32 degrees
Peak Cohesion	0 kPa
Material Behaviour	Drained
Fluid Bulk Modulus	2.2e+06 kPa

Table 5 Panel Properties used in Rs2 model

Color		
Liner Type	Reinforced Concrete	
Equivalent Young's modulus	2.06956e+07 kPa	
Equivalent thickness	1.38754 m	
Poisson ratio	0	
Panel Properties		
Type	I-beam(W): W1100 x 499	
Spacing	0.6 m	
Section Depth	1.12 m	
Area	0.0635 m2	
Moment of inertia	0.0129 m4	
Young's modulus	2e+08 kPa	
Poisson ratio	0.25	
Compressive strength	400000 kPa	
Tensile strength	400000 kPa	
Concrete Properties		
Thickness	0.2 m	
Young's modulus	3e+07 kPa	

Poisson ratio	0.15
Compressive strength	40000 kPa
Tensile strength	3000 kPa
Axial strain	0

Table 6 Joint Properties (Geostrip)

Joint Color	
Slip Criterion	None
Normal Stiffness	100000 kPa/m
Shear Stiffness	10000 kPa/m
Initial Deformation	Yes
Apply Pore Pressure	Yes
Apply Additional Pressure inside Joint	No
Apply Pressure to Liner Side Only	No
Apply Stage Factors	No

Table 7 Structural interface property

Structural Interface:	Structural 1
Joint (positive side):	Joint 1
Liner:	Panel
Joint (negative side):	Joint 1

Since the objective was to evaluate the stability of the left-hand side (LHS) of the RE wall only, the right-hand side (RHS) was modelled with appropriate boundary conditions to constrain displacement. Specifically:

- RHS boundary: Restrained in the X-direction
- Base boundary: Restrained in both X and Y directions

- LHS boundary: Left free to move in any direction to simulate real behaviour under loading

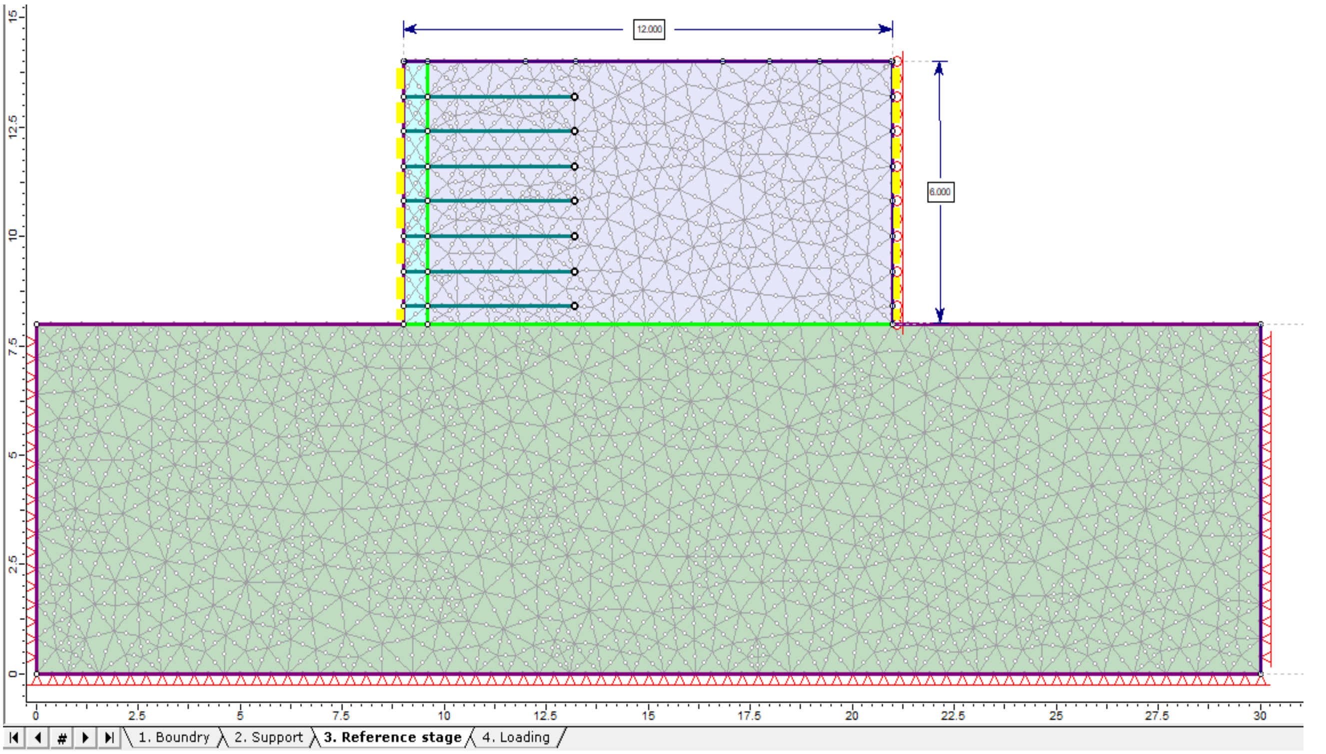

Figure 4.9 Static boundary condition with filter media and Geostrip

4.3 Meshing and Discretization

A structured mesh was generated, with approximately 1200 nodes to ensure sufficient resolution for capturing stress distribution and displacement behaviour. The mesh was refined around the RE wall and reinforcement zones to improve the accuracy of the results, particularly near areas of interest such as the reinforcement-soil interface and wall face.

Mesh Type: Uniform

Element Type: 6 Nodes Triangles

Table 8 Nodes used in RS2

Mesh type:	Uniform	
Element type:	6 Noded triangles	
Stage Name	# of Elements	# of Nodes

1. Boundry	2049	4293
2. Support	2049	4293
3. Reference stage	2049	4293
4. Loading	2049	4293

4.4 Loading and Analysis

Following meshing, the model was subjected to two stages of analysis:

1. Static Analysis: To establish baseline stresses and displacements under self-weight and static conditions.
2. Dynamic Analysis: Simulated using an impact load applied at the top portion of the RE wall, in accordance with experimental impact loading magnitudes.

6.5 Results and Observations

Post-analysis, the output parameters of interest were:

- Horizontal displacement along the height of the RE wall
- Shear stress distribution along a defined query line, placed vertically at the wall face

These results were used to compare with the physical model findings, providing validation and deeper insight into the behaviour of the RE wall under impact loading.

Table 9 Iteration Information

Maximum Number of Iterations:	500
Tolerance:	0.001
Number of Load Steps:	Automatic
Convergence Type:	Comprehensive
Tensile Failure:	Reduces Shear Strength
Joint tension reduces joint stiffness by a factor of 0.01	

4.5 Dynamic Modelling in RS2: Boundary Conditions and Material Properties

To replicate the actual site conditions and analyse the reinforced earth (RE) wall under dynamic loading, a numerical model was developed in RS2. The model geometry reflected real-world dimensions, comprising a 6 m high RE wall and a 12 m wide section placed on a compacted foundation bed of 30 m × 60 m, which was modelled with a higher density than the backfill to simulate a stiffer base.

A dense mesh of approximately 1200 nodes was generated to ensure accurate resolution of stress distribution, impact effects, and displacement propagation.

4.5.1 Material Properties

The filter media used in the RE wall was composed of a site-based well-graded mix (30% 20 mm aggregate, 23% 10 mm aggregate, and 27% crusher dust), selected to facilitate drainage while preventing fine particle migration. In the RS2 model, this filter media was modelled as a non-plastic, granular material using the Mohr-Coulomb failure criterion. The material parameters were:

- Cohesion (c): 0 kPa (cohesionless)
- Friction Angle (ϕ): 34°
- Unit Weight (γ): 18.47 kN/m³ (from Modified Proctor Test)
- Elastic Modulus (E): Calibrated to compaction level
- Poisson's Ratio (ν): 0.3

Though composed of mixed particle sizes, the absence of plasticity ensured that the material exhibited frictional, granular behaviour ideal for dynamic simulation.

4.5.2 Boundary Conditions for Dynamic Analysis

To simulate impact loading and reduce wave reflection artifacts, the following boundary conditions were implemented:

- Base Boundary: Absorbent boundary to allow stress wave dissipation.
- Filter Media Sides: Treated with absorbent (viscous) boundaries to mimic energy dissipation.

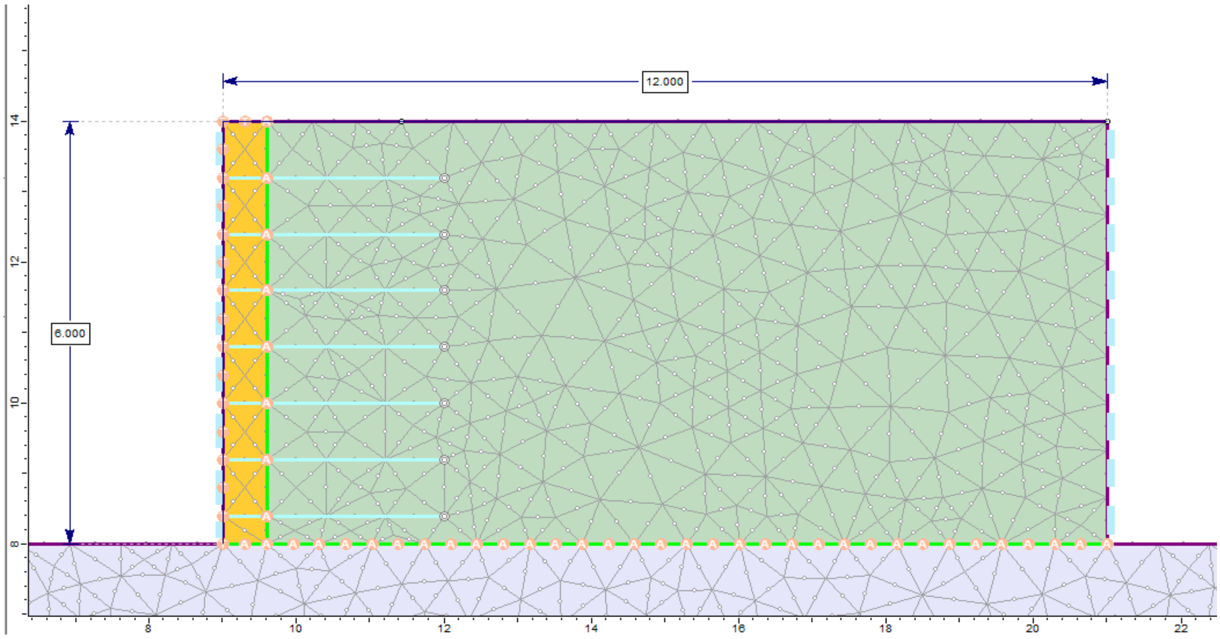

Figure 4.10 Dynamic Boundary condition

- Rear of RE Wall (LHS Observation Side): Modelled with transmitting boundaries to simulate lateral wave travel and reduce confinement effects.
- Right-Hand Side (RHS): Restrained in the x-direction to mimic lateral support from adjoining structures.
- LHS Side: Left free, enabling full deformation and dynamic response monitoring.

These boundaries ensure more realistic deformation behaviour and better capture of horizontal displacement and shear under dynamic conditions.

Simulation Stages and Reinforcement Variation

The RS2 dynamic analysis was carried out in three distinct stages:

1. Stage 1 – Static Equilibrium: Initial compaction and material self-weight application
2. Stage 2 – Dynamic Load Application: Impact loading simulated over 1.4 seconds
3. Stage 3 – Post-Impact Response: Continued observation of displacement and stress redistribution over 2.0 seconds. (This stage is on hold for future study)

Multiple trials were conducted to study the influence of reinforcement length and filter media behaviour:

- Geostrip lengths of 0.3H, 0.5H, and 0.7H were used across simulations.

- An additional trial with scaled-down filter media (maintaining site mix proportions) was conducted using the same dynamic loading conditions.

4.5.3 Time History Function and Results Interpretation

A custom time history function was applied to simulate the loading impulse generated during impact tests, replicating the loading patterns observed in the physical model. This time history allows for accurate modelling of transient stresses and displacements over time.

Table 10 Time History function for dynamic loading

Time (s)	2.5kg_10cm	2.5kg_30cm	3.5kg_10cm	3.5kg_30cm	8.0kg_10cm	8.0kg_30cm
0	0	0	0	0	0	0
0.01	58	173	81	242	185	554
0.05	58	173	81	242	185	554
0.5	0	0	0	0	0	0
0.51	58	173	81	242	185	554
0.55	58	173	81	242	185	554
1	0	0	0	0	0	0
1.01	58	173	81	242	185	554
1.05	58	173	81	242	185	554
1.5	0	0	0	0	0	0
1.51	58	173	81	242	185	554
1.55	58	173	81	242	185	554
2	0	0	0	0	0	0
2.01	58	173	81	242	185	554
2.05	58	173	81	242	185	554

This time history function gives small amount of change in the loading so only three loading condition has been considered for dynamic analysis. 58kPa, 173kPa, 554kPa and comparative graph has been plotted for the same.

- Horizontal displacement vs. time response along the wall height
- Shear stress variation with depth

- Comparison of results across trials with varying reinforcement lengths and filter media

These insights allow for a detailed understanding of the RE wall's resilience and dynamic behaviour under repeated loading, supporting recommendations for safe design and material selection in real-world applications.

4.5.4 Formulas used in the Dynamic condition [16]

(a) Considering a dynamic system:

$$[M]\left(\frac{dy^2}{dx^2}\right) + [C]\left(\frac{dy}{dx}\right) + [K]\big(x(t)\big) = F_{(stat)} + F(dyn)$$

(14)

Where C is the Reyleigh damping

$$[C] = (\alpha_M)[M] + (\beta_K)[K] \quad (15)$$

Where α_m and β_k

Are constants with the units of $s^{-1}$and s respectively [K] is the linear stiffness matrix of the structure

The matrix [K] represents the linear stiffness of the structure, established using the initial tangent stiffness values. The damping matrix [C] is typically composed of two components: one proportional to the mass and the other proportional to the stiffness.

To determine the coefficients α_M and β_K suitable damping values are selected, ideally targeting specific modes of the linear system as described by Equation (1).

(b) Impact force (Average force estimation)

To convert the average impact force

$$F = m.\frac{\Delta v}{\Delta t}$$

(16)

Or $F = \frac{E}{d}$

(c) Dynamic Load Factor (DLF)

For approximating dynamic effect on static analysis:

$$DLF = \frac{F_{dynamic}}{F_{static}} \tag{17}$$

Typically, the value of DLF varies from **1.5 to 3** are used for moderate to high impacts. This helps convert impact loads into equivalent static loads in RS2.

(d) Shear stress from impact load

Once the force is known, shear stress on a contact surface is given by:

$$\tau = \frac{F}{A} \tag{18}$$

(e) Displacement and stress Analysis (FEM-Based)

RS2 solves the Equilibrium Equations numerically using:

$$[M].\{\ddot{u}\} + [C].\{\dot{u}\} + K.\{u\} = \{F(t)\} \tag{19}$$

This equation balances inertia, damping, stiffness and external loads it is solved using time stepping methods like Newmark-bet, Wilson θ or explicit schemes.

CHAPTER 5

RESULT

5.1 Experimental results

5.1.1 Particle size distribution

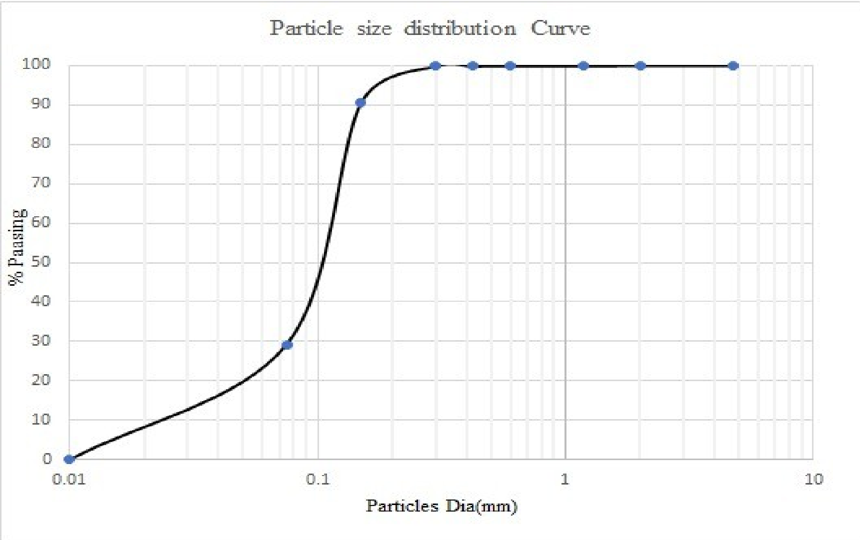

Figure 5.1 Particle size distribution analysis curve

Table 11 Uniformity coefficient and curvature of soil sample

Parameters	Values
$D_{(10)}$(mm)	0.023
$D_{(30)}(mm)$	0.076
$D_{(60)}$(mm)	0.113
Uniformity Coefficient $C_u = \frac{D_{60}}{D_{10}}$	**5.004**
Curvature Coefficient $C_c = \frac{(D_{30})^2}{(D_{60} X D_{10})}$	**2.275**

5.1.2 Specific Gravity test

Table 12 Specific gravity

		Sample 1	Sample 2
Mass of Density bottle	$\boldsymbol{M_1}$ $(\boldsymbol{mm})$	35.168	35.504
Empty Density bottle +dry soil	$\boldsymbol{M_2}$ $(\boldsymbol{gm})$	42.181	42.50
Empty Density Bottle +dry Soil + water	$\boldsymbol{M_3}$ $(\boldsymbol{gm})$	90.078	90.382
Empty Density bottle +water	$\boldsymbol{M_4}(\boldsymbol{gm})$	85.607	85.957
Specific Gravity	**G**	2.758	2.715

Average Value Of specific Gravity of the soil sample = (2.758+2.715)/2

=2.7365

5.1.3 Compaction Test

Table 13 Water Content and dry Density relation for compaction

S.N.	Dry Density,γ_d (kN/m^3)	Water Content, w (%)
1	1.757	4.60
2	1.783	6.26
3	1.711	7.25
4	1.826	9.99
5	1.847	11.52

6	1.77	13.56
7	1.71	15.45

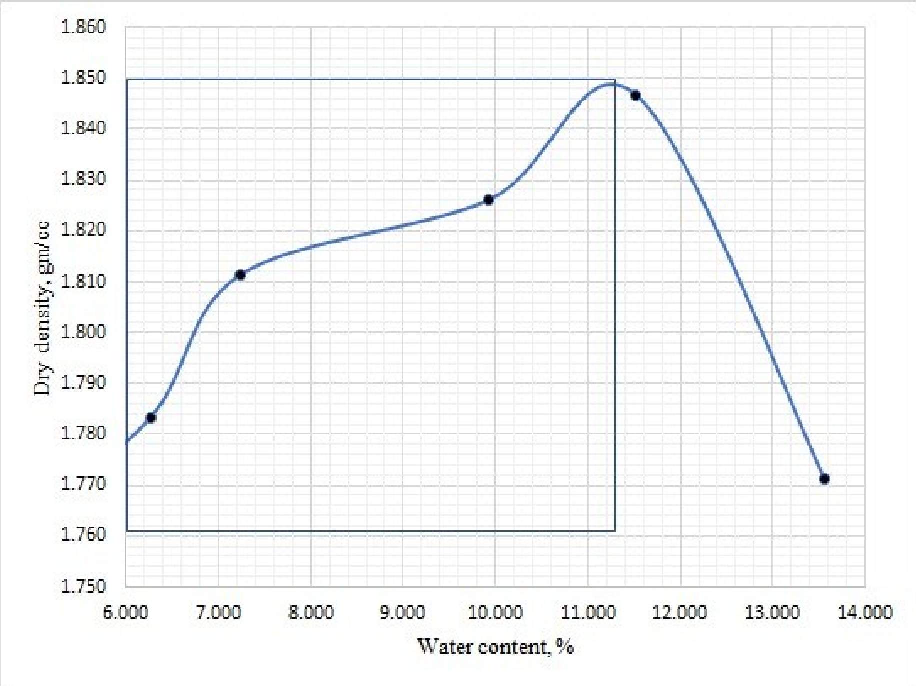

Figure 5.2 Variation of Dry density wit moisture content

Table 14 Result of Compaction test

	OMC	MDD, $\gamma_{d\ max}$	Compressibility Bulk density, γ_b
Soil Sample	11.517	1.847	1.656

Table 5.1.4 Direct Shear Test

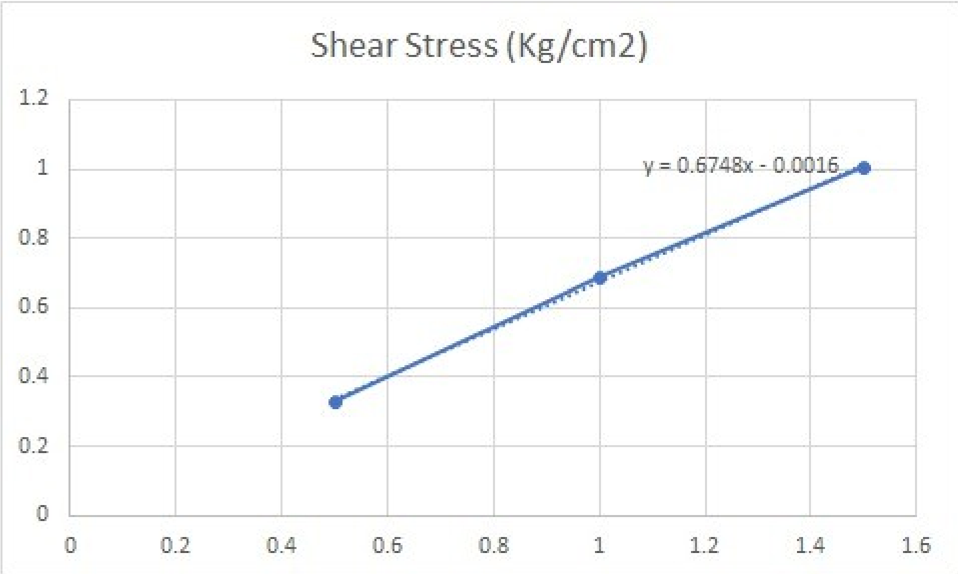

Figure 5.3 Mohr-Coulomb Failure envelope

Table 15 Values of cohesion (C) and Internal Friction Angle (ϕ)

Cohesion (g/cm^2)	0.0016
Internal Friction Angle (°)	34.0114

5.1.5 Gradation Test For filter media

Table 16 Gradation test

SR No	IS Sieve Size (mm)	Weight Retained (gm)	Cum. Weight Retained (gm)	% Weight Retained	(%) Passing	MORT & H Sec-300 Table No-300-3 Class 2
1	26.5	0	0	0	100	100
2	22.4	65	65	0.22	99.78	95-100
3	11.2	8910	89.75	30.60	69.40	48-100

4	5.6	8944	17969	61.26	38.74	28-54
5	2.8	4418	22387	76.33	23.67	20-35
6	0.71	3156	25543	87.09	12.91	6-18
7	.355	2525	28068	95.70	4.31	2-9
8	.09	1105	29173	99.46	0.54	0-4
9	Pan					

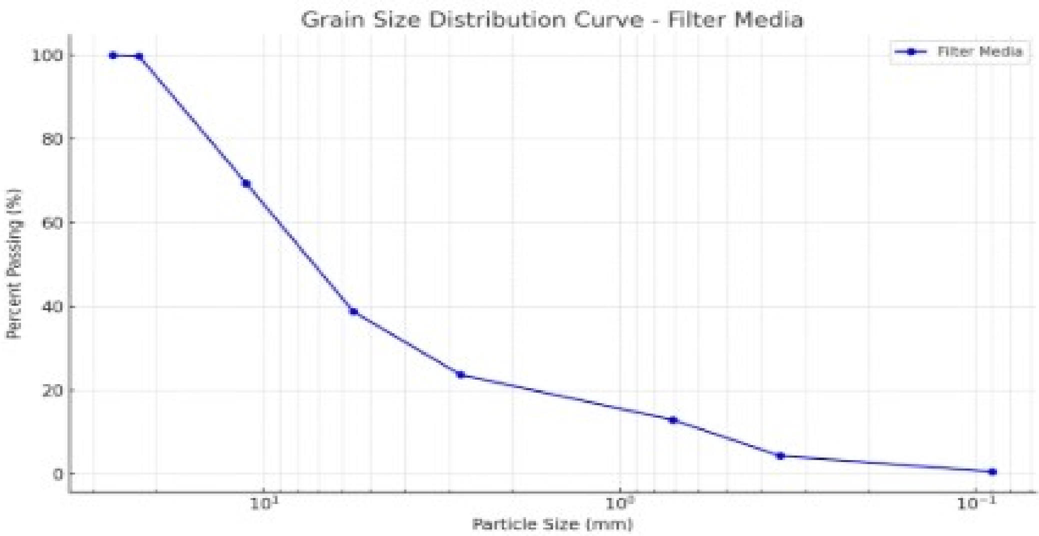

Figure 5.4 Gradation Curve

Table 17 Soil Properties

SR	Name of parameter	Observed value	Test method
1	Direct shear test		IS 2720 Pt-13
a	C Value, Kg/cm2	0.00016	
b	**Φ** Value, Degree (”)	34	
3	Plastic Limit, %	NP	IS:2720 Pt-05
4	OMC, %	11.517	IS:2720 Pt-08
5	MDD, g/cc	1.847	IS:2720 Pt-08
7	Gradation		
	Sieve Size (mm)	% Passing	
	4.75	100	
	0.425	99.89	
	.075	29.247	

5.2 Scaled Model Study (Dynamic Loading)

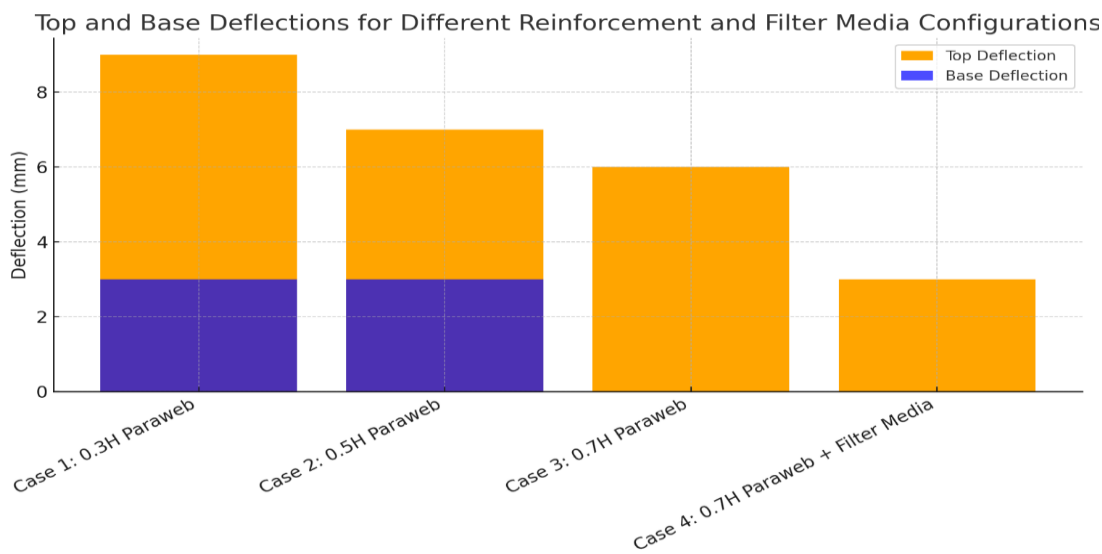

Figure 5.5 Top and bottom deflection

Table 18 Physical model Wall Displacement Varying Reinforcement Length vs Constant Load

Trial Description	Reinforcement Length	Impact Load	Drop height (cm)	Number of impacts	Top deflection (mm)	Base deflection (mm)
Case 1 0.3H Geostrip	0.3	8.38	50	3	9	3
Case 2: 0.5H Geostrip	0.5	8.38	50	3	7	3
Case 3: 0.7H Geostrip	0.7	8.38	50	5	6	0
Geostrip +Filter media	0.7	8.38	50	3	3	0

The experimental results highlight the influence of geostrip reinforcement length and the addition of filter media on the structural response to impact loading. Increasing the reinforcement length from 0.3H to 0.5H and then to 0.7H progressively reduced the top deflection from 9 mm to 7 mm and finally to 6 mm. Notably, the 0.7H reinforcement configuration also eliminated base deflection entirely, demonstrating enhanced stability. The most significant improvement was observed when a filter media was combined with the 0.7H geostrip reinforcement: this configuration achieved the lowest top deflection of 3 mm and zero base deflection, even with fewer applied impacts compared to the 0.7H case without filter media. These findings suggest that both increasing the reinforcement length and incorporating filter media are effective strategies for minimizing structural deformation under dynamic loading conditions.

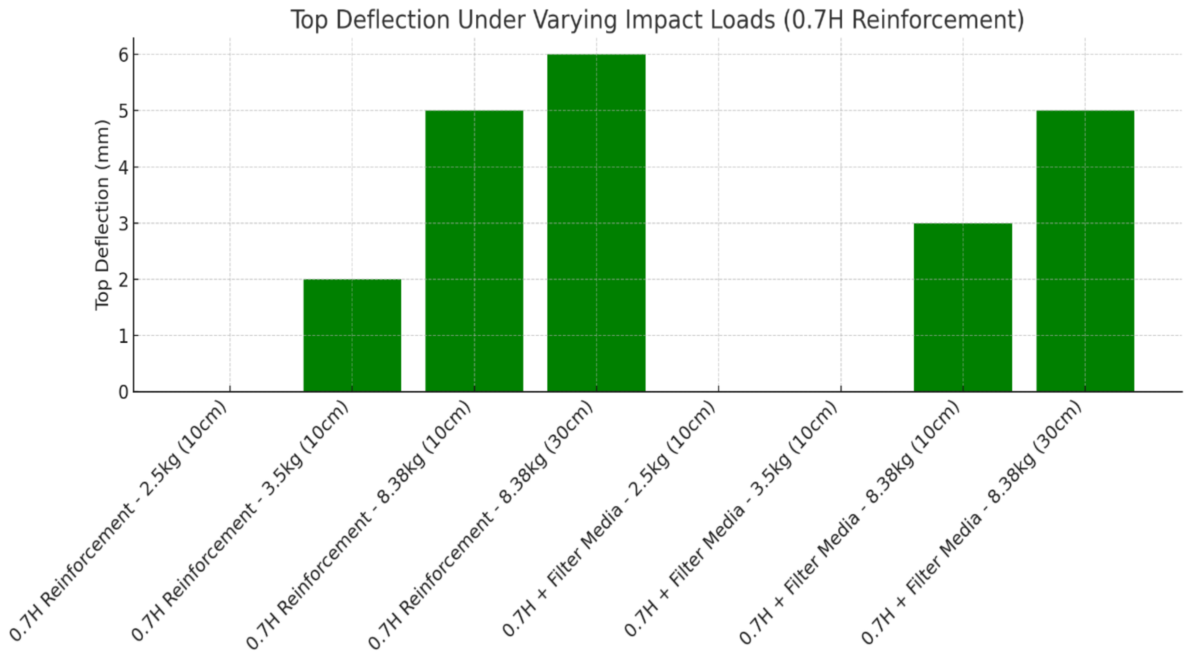

Figure 5.6 Deflection under various load

Table 19 Physical Model Wall Displacement in 0.7h Reinforcement vs Varying Load

Trial description	**Top deflection (mm)**
0.7H Reinforcement-2.5kg (10cm	0
0.7H Reinforcement -3.5kg(10cm)	2
0.7H Reinforcement -8.38 kg- (10cm)	5
0.7H Reinforcement –(10cm)	6
0.7H Reinforcement +filter media -2.5 kg	0
0.7H Reinforcement + Filter media -3.5 kg	3
0.7H Reinforcement +Filter Media-8.38 kg (10cm)	3
0.7H Reinforcement + Filter Media -8.38 (30cm)	5

The results demonstrate the effectiveness of combining 0.7H geostrip reinforcement with filter media under varying impact conditions. For configurations using 0.7H reinforcement alone deflection increased with impact severity: a 2.5 kg mass dropped from 10 cm caused no deflection (0 mm), while heavier masses (3.5 kg and 8.38 kg) at the same height resulted in 2 mm and 5 mm deflections, respectively. The baseline 0.7H reinforcement (no filter media) with unspecified mass at 10 cm exhibited the highest deflection (6 mm). Introducing filter media significantly improved performance: at 10 cm drop height, the 2.5 kg mass with filter media maintained zero deflection, and the 3.5 kg and 8.38 kg masses limited deflection to 3 mm. However, increasing the drop height to 30 cm for the 8.38 kg mass with filter media increased deflection to 5 mm, matching the deflection observed without filter media at 10 cm. These findings indicate that filter media enhances load distribution and reduces deflection at lower impact energies (10 cm drop) but becomes less effective as impact energy increases (30 cm drop), emphasizing the need to optimize drop height when pairing geostrip reinforcement with filter media.

5.3 Numerical Modelling

In the case of numerical modelling we have applied the load only on the 1.8 of the top of the wall at a 1m offset since it replicates the IRC-56 guidelines. For Both cases

5.3.1 Static Condition

1.1 Observation of Horizontal Displacement

To evaluate the horizontal displacement behaviour of the MSE wall, a query line was generated along the height of the wall within the RS2 numerical model. This query line remained consistent for both static and dynamic load simulations to enable direct comparison of displacement profiles under different loading conditions.

In the static loading case, the experimentally derived impact forces were converted into equivalent static tyre pressures, following the guidelines specified in IRC: 58–2015**.** This conversion was based on the standard tyre contact area recommended by the code, typically taken as 0.02 m² per wheel for heavy commercial vehicles. The calculated pressure was then uniformly distributed over the designated load area at the surface of the wall to simulate static axle loads under real traffic conditions.

This consistent approach allowed for a comparative analysis of horizontal wall displacements between the static and dynamic scenarios, providing valuable insight into the reinforcement effectiveness, load transfer behaviour, and overall structural stability under realistic traffic-induced forces.

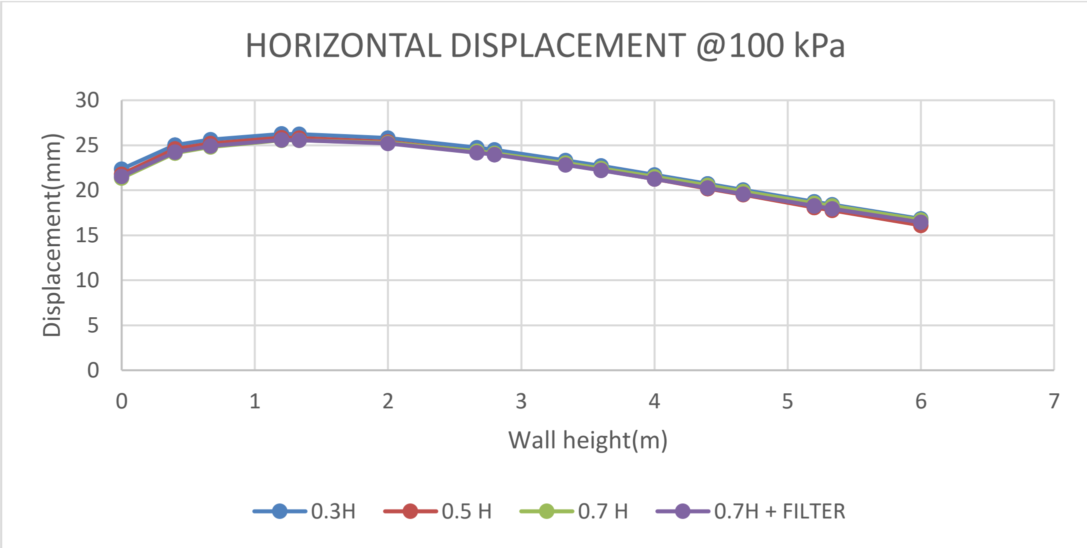

Figure 5.7 Horizontal displacement at 100 kPa

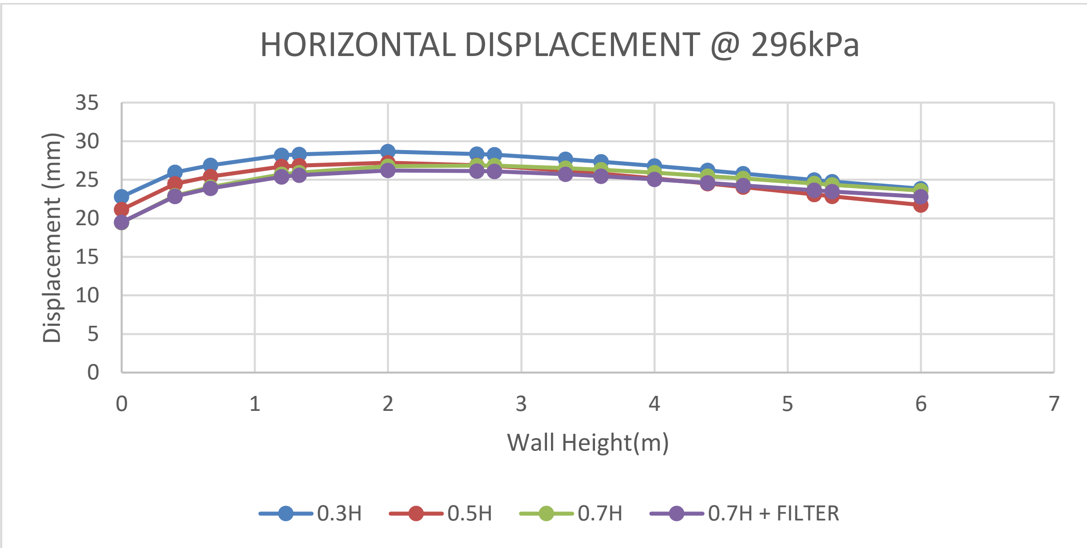

Figure 5.1 Horizontal displacement at 296 kpa

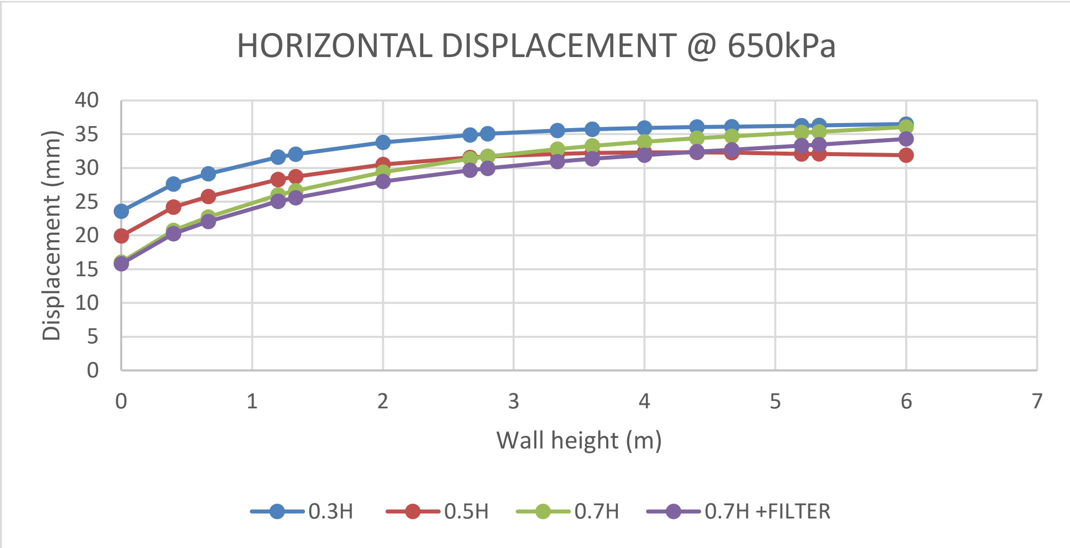

Fig 5.2 Horizontal displacement At 650 kPa

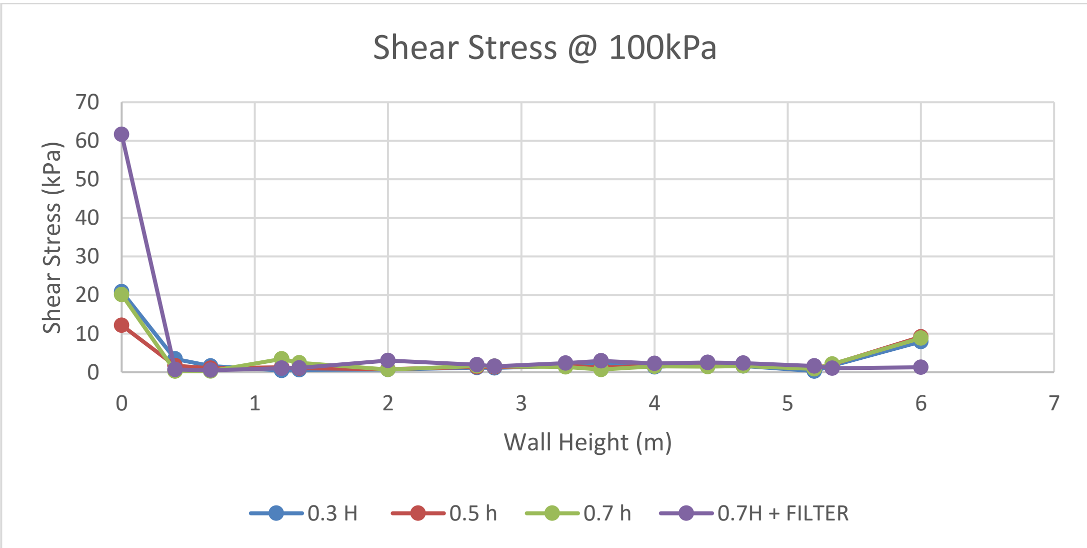

Figure 5.2 Shear stress at 100 kPa

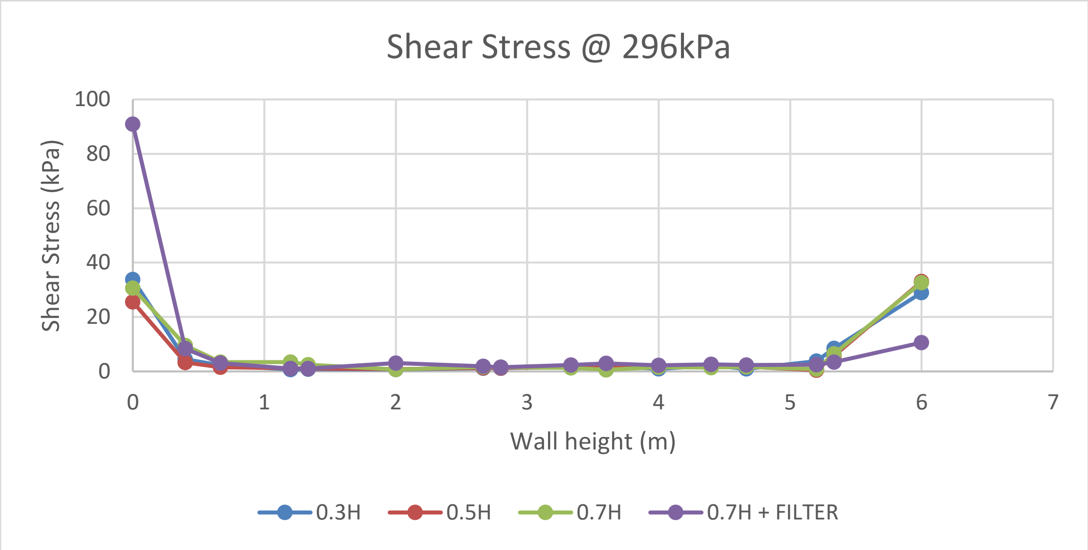

Figure 5.3 Shear stress at 296 kPa

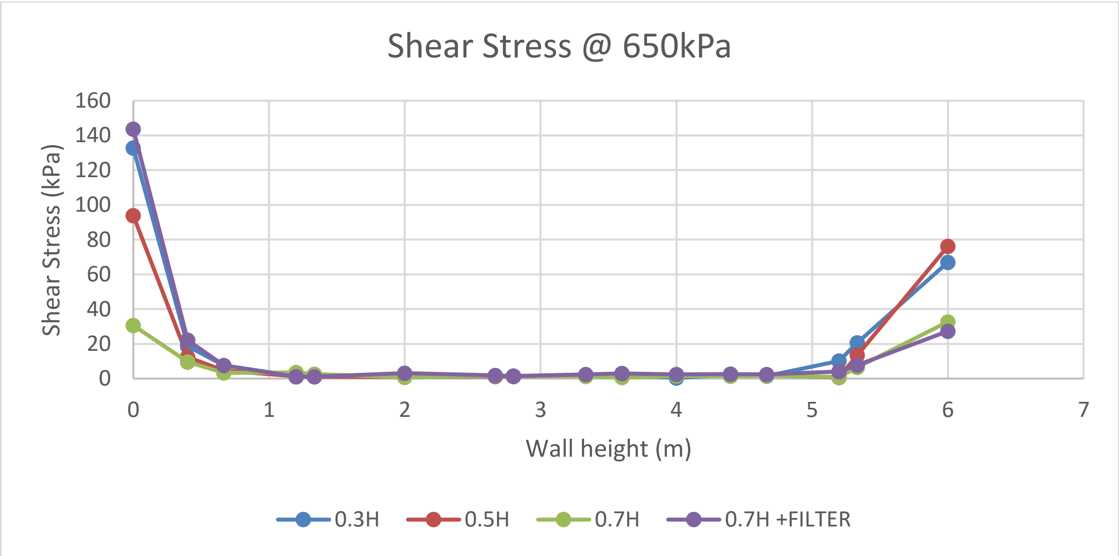

Figure 5.4 Shear stress at 650 kPa

1.2 Interpretation of static result

2.1. (0.3h) Reinforcement

(a) 100 kN/m² loading

- Horizontal displacement ranges from ~22.4 mm to 28.2 mm as wall height increases.
- Shear stress starts high at the base (~23.6 kPa) and decreases rapidly with height.
- Interpretation: At low load, short reinforcement provides some stability, but displacement increases with wall height, and stress is not well distributed.

(b) 296 kN/m² loading

- Horizontal displacement increases to ~25.0–28.6 mm.
- Shear stress at the base is much higher (~33.8 kPa) but drops sharply with height.
- Interpretation: As load increases, the wall with 0.3h reinforcement shows greater displacement and high stress concentration at the base, indicating limited effectiveness.

(c) 650 kN/m² loading

- Horizontal displacement further increases, reaching up to ~36.5 mm at the top.
- Shear stress at the base is highest (~36.5 kPa) but falls off rapidly.
- Interpretation: At high load, short reinforcement is insufficient—displacement and stress concentration are significant, indicating a high risk of pullout or failure.

2.2. (0.5h) Reinforcement

(a) 100 kN/m² loading

- Horizontal displacement is similar to 0.3h, ~21.1–27.2 mm.
- Interpretation: Slight improvement over 0.3h, but not substantial at low load.

(b) 296 kN/m² loading

- Horizontal displacement increases significantly, up to ~93.9 mm at the base.
- Shear stress is relatively low and decreases with height.
- Interpretation: Under moderate load, 0.5h reinforcement is not sufficient to control displacement, especially at the base, suggesting a risk of compound sliding.

(c) 650 kN/m² loading

- Horizontal displacement ranges from ~19.9 mm (base) to ~36.1 mm (top).
- Interpretation: Performance is better than 0.3h but still not adequate for high loads; displacement remains high.

2.3. (0.7h) Reinforcement

(a) 100 kN/m² loading

- Horizontal displacement is lowest, ~16.4–25.6 mm.
- Shear stress is more evenly distributed with height.
- Interpretation: Longer reinforcement significantly improves stability at low load, with lower displacement and better stress distribution.

(b) 296 kN/m² loading

- Horizontal displacement is well controlled, ~19.4–26.8 mm.
- Shear stress remains higher and more consistent with height.
- Interpretation: At moderate load, 0.7h reinforcement effectively limits displacement and distributes stresses, reducing risk of failure.

(c) 650 kN/m² loading

- Horizontal displacement ranges from ~16.0 mm (base) to ~36.1 mm (top).
- Shear stress at the base is very high (~122.5 kPa), but the reinforcement maintains stability.
- Interpretation: Even at high load, 0.7h reinforcement provides the best performance among all lengths, minimizing displacement and localizing stress.

2.4. (0.7h) Reinforcement with Filter Media (at 100, 296, 650 kN/m²)

(a) 100 kN/m² loading

- Horizontal displacement is further reduced (~19.5–25.6 mm).
- Shear stress is slightly lower than without filter, but more uniform.
- Interpretation: Filter media slightly improves displacement control and stress uniformity.

(b) 296 kN/m² loading

- Horizontal displacement is ~19.5–26.1 mm, generally lower than without filter.
- Shear stress is higher and more evenly distributed.
- Interpretation: Filter media enhances the effect of 0.7h reinforcement, further reducing displacement and improving stress distribution.

(c) 650 kN/m² loading

- Horizontal displacement is ~15.8–34.3 mm, consistently lower than without filter.
- Shear stress is higher and more uniform.

- Interpretation: Filter media is most effective under high load, significantly reducing displacement and helping maintain wall stability.

Table 20 Numerical Modelling Static Case Scenario

Case	100kN/m2	296kN/m2	650kN/m2	Performance Trend
0.3h	22-28mm	25-29mm	27-36mm	High displacement and stress concentration at higher loads; not recommended for moderate/high loading.
0.5h	21-27mm	24-94mm	20-36mm	Slight improvement; still inadequate for moderate/high loads.
0.7h	16-26mm	19-27mm	16-36mm	Best performance; low displacement and good stress distribution at all loads.
0.7h + Filter	19-26mm	19-26mm	16-34mm	Further reduces displacement and improves stress uniformity, especially at high load.

Overall Interpretation

- Increasing the reinforcement length from 0.3h to 0.7h significantly improves RE wall stability under all static loading conditions, reducing both displacement and stress concentration.
- The use of filter media with 0.7h reinforcement further enhances performance, especially at higher loads, by reducing horizontal displacement and promoting more uniform stress distribution.
- Shorter reinforcements (0.3h, 0.5h) are not recommended for moderate to high loads due to excessive displacement and risk of failure.
- For optimal stability and safety, especially under higher loading, a reinforcement length of 0.7h with filter media is strongly recommended.

5.3.2 Max horizontal displacement with varying loading

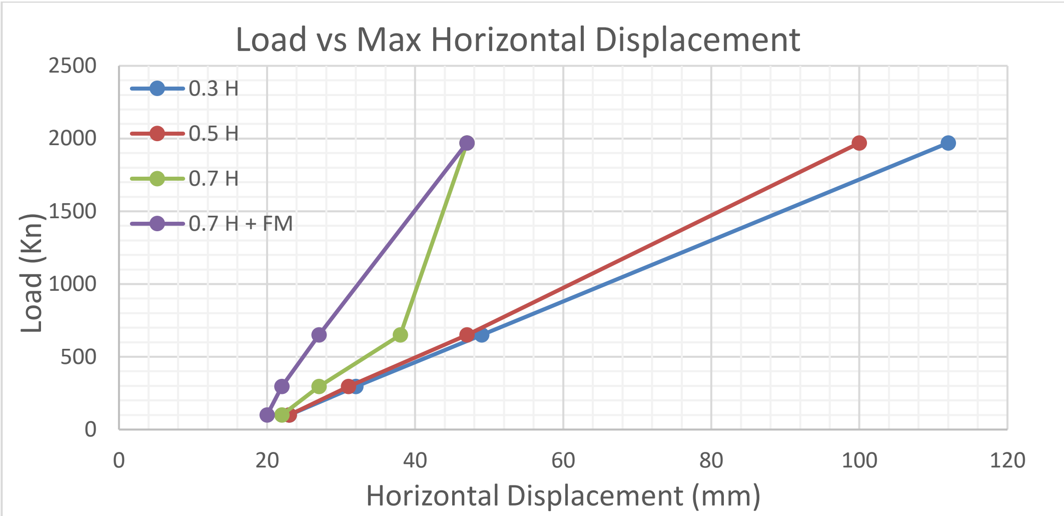

Fig. no. 5.5 Max horizontal displacement Vs load

The analysis of reinforced earth (RE) wall stability under varying reinforcement lengths (0.3h, 0.5h, 0.7h) and loading conditions (100–1970 kN/m²) reveals critical mechanical behaviour patterns.

2.1. Data Overview

a. Reinforcement Configurations: 0.3h, 0.5h, 0.7h (without filter media) 0.7h + Filter (with filter media)

b. Loading Conditions: 100, 296, 650, 1970 kN/m²

c. Parameters Analysed: Effect of loading condition on horizontal displacement performance.

Table 21 Max. Horizontal displacement Static Case Scenario

Case	Horizontal Disp (mm) at 100kN/m2	Horizontal Disp (mm) at 296kN/m2	Horizontal Disp (mm) at 650kN/m2	Horizontal Disp (mm) at 1970kN/m2

0.3h (mm)	23	32	49	112
0.5h (mm)	23	31	47	100
0.7h (mm)	22	27	38	47
0.7h+Filter (mm)	20	22	27	47

2.2 Key Insight:

- Filter media reduces horizontal displacement by 13% and total displacement by 85% compared to 0.7h alone at 100kN/m2 loading.
- 0.7h + Filter limits horizontal displacement to 22 mm (31% lower than 0.3h) at 296 kN/m2 loading.
- Filter media reduces horizontal displacement by 29% at 650kN/m2 loading
- 0.7h (with/without filter) halves displacement compared to 0.5h at 1970kN/m2 loading.

2.3 Failure Mechanism Analysis

Table 22 Failure Mode Static Case Scenario

Load (kN/m²)	**Dominant Failure Mode**	**Critical Configuration**
100	Base sliding	0.3h/0.5h
296	Compound sliding	0.3h/0.5h
650	Internal pullout	0.3h/0.5h
1970	Global collapse	0.3h/0.5h

2.4 Design Implications

(a). Reinforcement Length: 0.7h is mandatory for loads ≥650 kN/m² to prevent pullout and collapse.≤0.5h configurations fail catastrophically at 1970 kN/m² (displacement ≥100 mm).

(b). Filter Media Efficacy: Reduces horizontal displacement by 13–29% and total displacement by 83–85% across loads. Critical for 0.7h under 650–1970 kN/m² to limit vertical settlement (e.g., 99 mm vs. 236 mm at 650 kN/m²).

(c). Load-Specific Recommendations: 100–296 kN/m²**:** 0.7h + Filter ensures stability (displacement ≤22 mm). ≥ 650 kN/m²**:** 0.7h + Filter is non-negotiable to avert collapse.

Summary

The data conclusively demonstrates that 0.7h reinforcement with filter media achieves optimal stability across all loading conditions, reducing displacements by up to 85% compared to shorter configurations. Shorter lengths (≤0.5h) exhibit progressive failure under high loads, emphasizing the need for rigorous adherence to reinforcement length guidelines in mechanically demanding environments. These results provide a quantitative foundation for RE wall design in practical applications.

5.3.3 Dynamic Condition

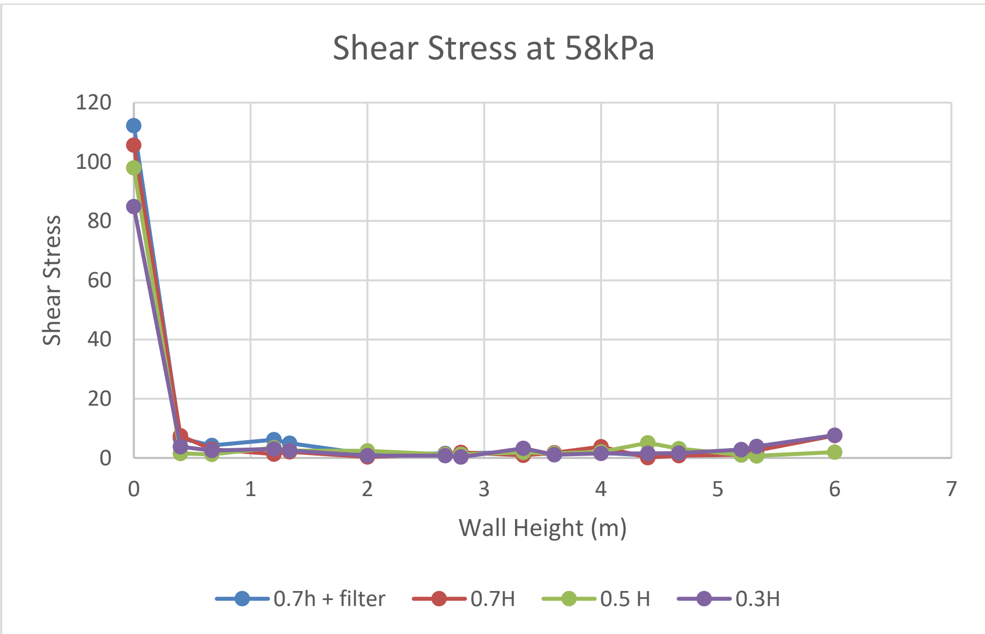

Figure 5.6 Shear stress at 58 kPa

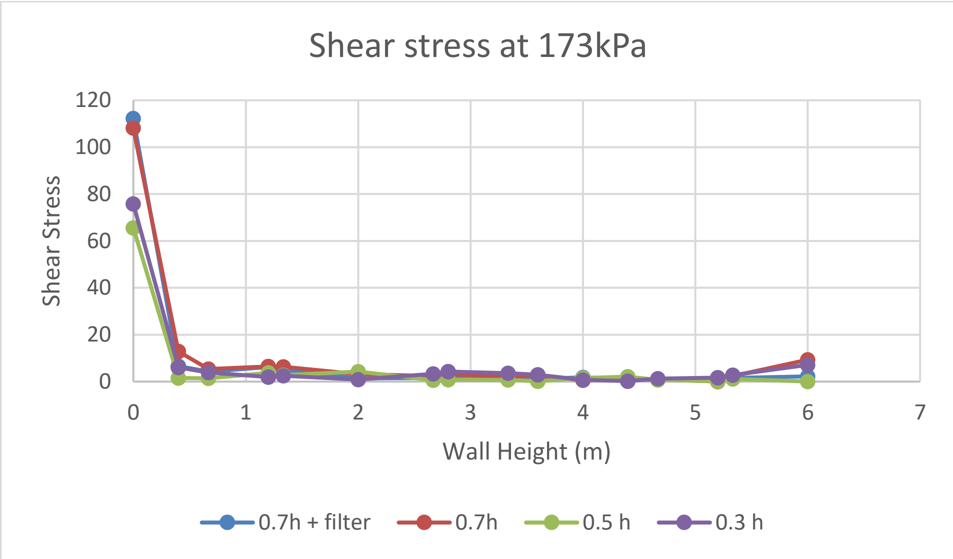

Figure 5.7 Shear stress at 173 kPa

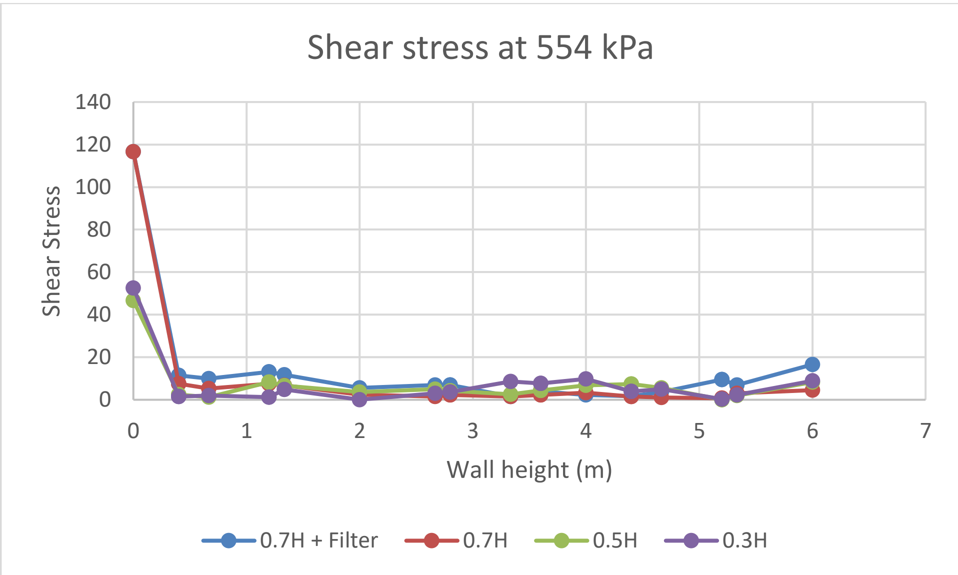

Figure 5.8 Shear stress at 554 kPa

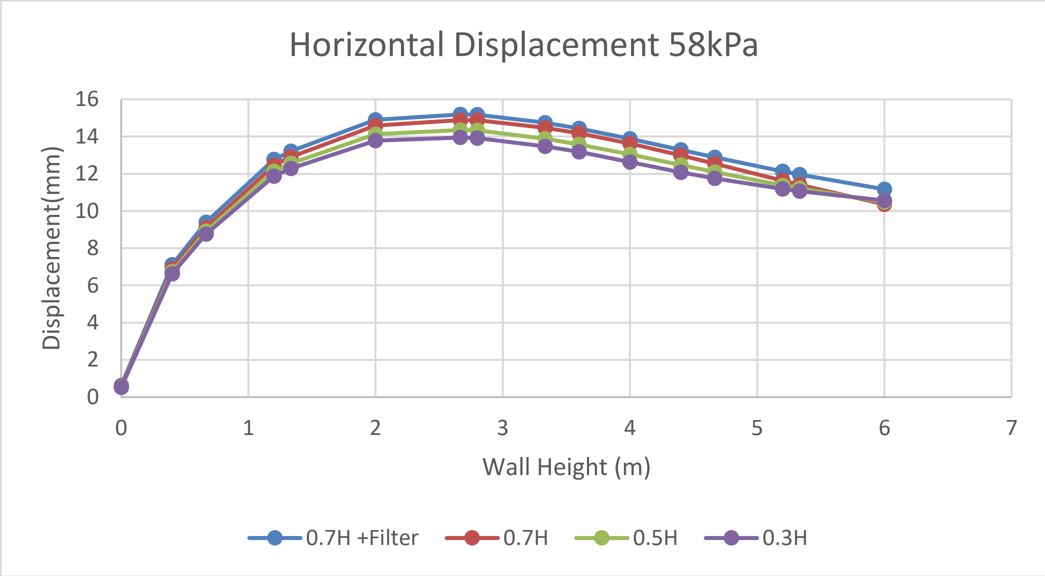

Figure 5.9 Horizontal displacement at 58kPa loading

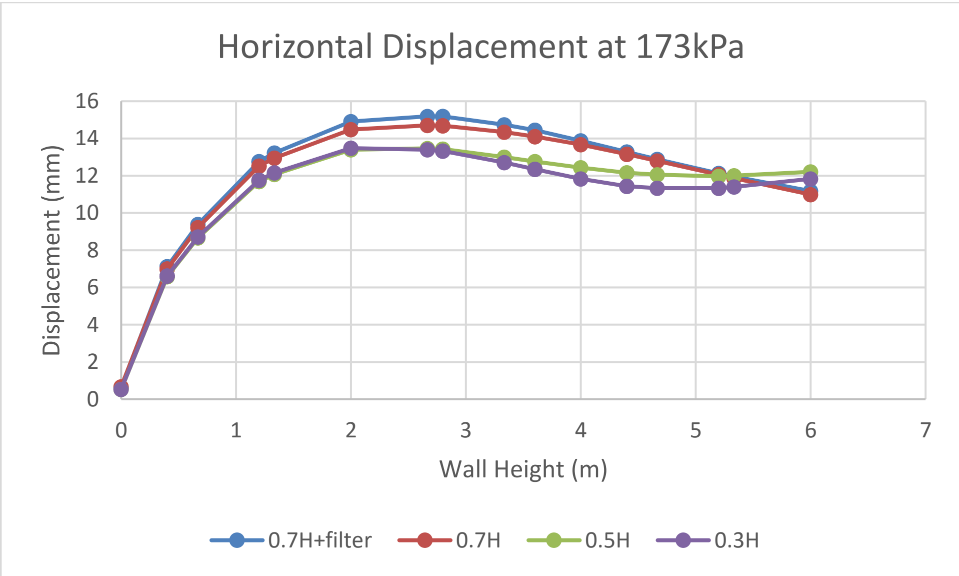

Figure 5.10 Horizontal displacement at 173kPa

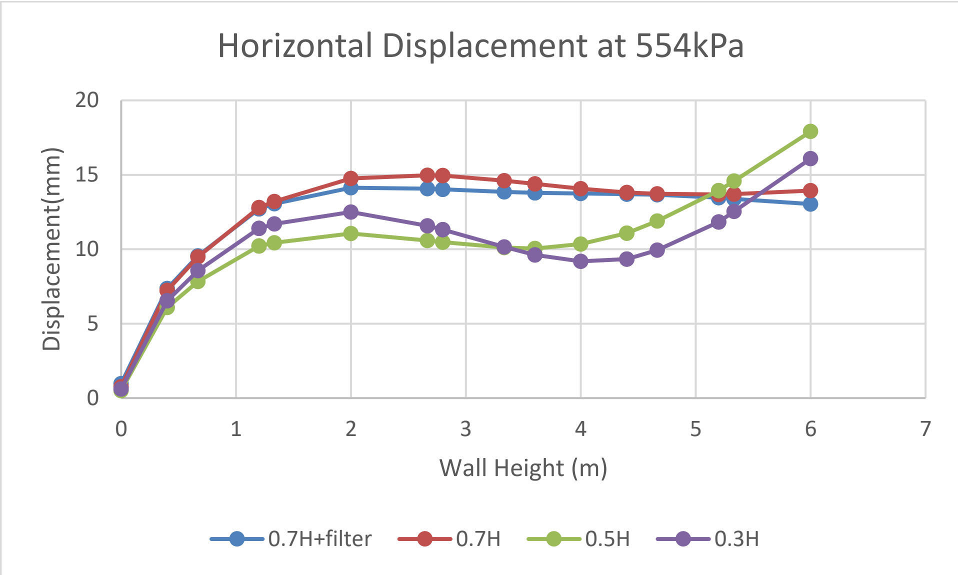

Figure 5.11 Horizontal displacement at 554 kPa

Dynamic Analysis of Reinforced Earth wall

The dataset evaluates RE walls under dynamic loads (58, 173, 554 kPa) for reinforcement lengths **0.3h, 0.5h, 0.7h** with/without filter media. Below is a structured analysis of displacement, shear stress, and failure modes for each configuration.

1. 0.3h Reinforcement

- 58 kPa**:**
  - Horizontal displacement**:** 6.63–8.75 mm (base to top).
  - Shear stress**:** Peaks at 84.86 kPa (base), decreasing to 3.78 kPa (top).
  - Behavior**:** Base sliding dominates due to poor stress distribution.
- 173 kPa:
  - Horizontal displacement**:** Increases to 11.40–12.53 mm.
  - Shear stress**:** Mid-height stress concentration **(**75.79 kPa**)** indicates transitional failure.
- 554 kPa**:**
  - Horizontal displacement**:** 36.51 mm (catastrophic).
  - Shear stress**:** Localized failure at mid-height **(**52.56 kPa**).**
  - Failure Mode**:** Global collapse due to insufficient reinforcement engagement.

2. 0.5h Reinforcement

- 58 kPa**:**

- Horizontal displacement: 6.58–8.91 mm.
- Shear stress: Moderate stress distribution (65.63 kPa at base).

- 173 kPa:
  - Horizontal displacement: 93.85 mm (base), indicating compound sliding.
  - Shear stress: Low and erratic (12.37 kPa), reflecting instability.
- 554 kPa:
  - Horizontal displacement: 10.22–36.51 mm.
  - Shear stress: 31.70 kPa (mid-height), insufficient for stress redistribution.

3. 0.7h Reinforcement

- 58 kPa:
  - Horizontal displacement: 6.88–9.55 mm.
  - Shear stress: Uniformly distributed (105.66 kPa at base).
- 173 kPa:
  - Horizontal displacement: 12.72–14.13 mm.
  - Shear stress: Stable redistribution (108.14 kPa at base).
- 554 kPa:
  - Horizontal displacement: 34.29 mm (top).
  - Shear stress: 116.65 kPa (base), demonstrating load-bearing capacity.

4. 0.7h + Filter Media

- 58 kPa:
  - Displacement: Reduced by 9% (19.45 mm vs. 21.35 mm without filter).
  - Shear stress: More uniform (98.30 kPa at base).
- 173 kPa:
  - Displacement: Reduced by 16% (22.83 mm vs. 27.21 mm).
  - Shear stress: Stress concentration mitigated (108.14 kPa → 98.30 kPa).
- 554 kPa:
  - Displacement: Reduced by 6% (34.29 mm vs. 36.51 mm).
  - Shear stress: Maintained stability despite extreme load (116.65 kPa).

Failure Mode Progression under Dynamic Loading

Table 23 Failure Mode Dynamic Case Scenario

Load (kPa)	**0.3h**	**0.5h**	**0.7h (+Filter)**
58	Base sliding	Base sliding	Stable
173	Mid-height shear	Compound sliding	Stress redistribution
554	Global collapse	Transitional failure	Localized deformation

Comparison with Static Loading

Table 24 Comparison Static Vs Dynamic

Parameter	**Static (650 kPa)**	**Dynamic (554 kPa)**
0.7h displacement	27.21 mm	34.29 mm (+26%)
Shear stress (peak)	122.45 kPa	116.65 kPa (-5%)
Filter efficacy	29% displacement reduction	6–16% reduction

Key Insights:

1. **Dynamic loads increase displacements** by 26% due to inertial forces and cyclic stress reversals.
2. **Filter media** is less effective under dynamic conditions but still critical for mitigating localized deformation.
3. **0.7h reinforcement** is indispensable in dynamic scenarios to prevent catastrophic failure.

Critical Design Implications

Reinforcement Length:

0.7h is mandatory for loads ≥173 kPa to ensure stress redistribution.

≤0.5h fails catastrophically under dynamic loads (e.g., 93.85 mm displacement at 173 kPa).

Filter Media:

Use geotextiles with **O95≤0.5D85O_{95} \leq 0.5D_{85}O95≤0.5D85** to prevent clogging.

Most effective at moderate loads (58–173 kPa), reducing displacement by **9–16%**.

Conclusion

Dynamic loading exacerbates displacement and stress concentration, but 0.7h reinforcement with filter media maintains stability by redistributing stresses. Shorter lengths (≤0.5h) are unsuitable for dynamic environments, emphasizing the need for rigorous adherence to reinforcement guidelines. These findings align with FHWA studies on MSE walls, which highlight the importance of stress management in flexible retaining systems.

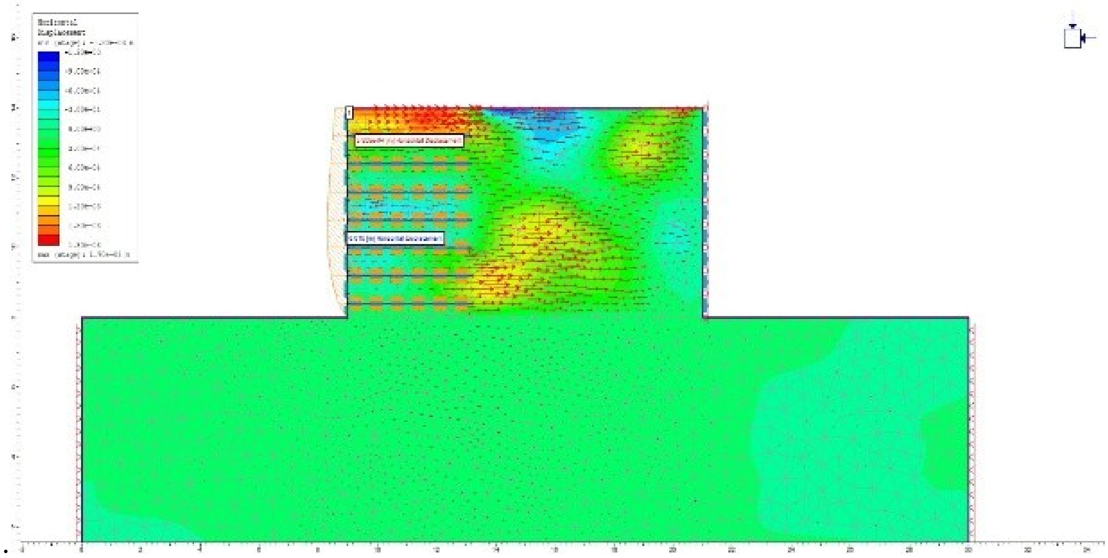

Figure 5.12 Deformed mesh under static loading and horizontal displacement

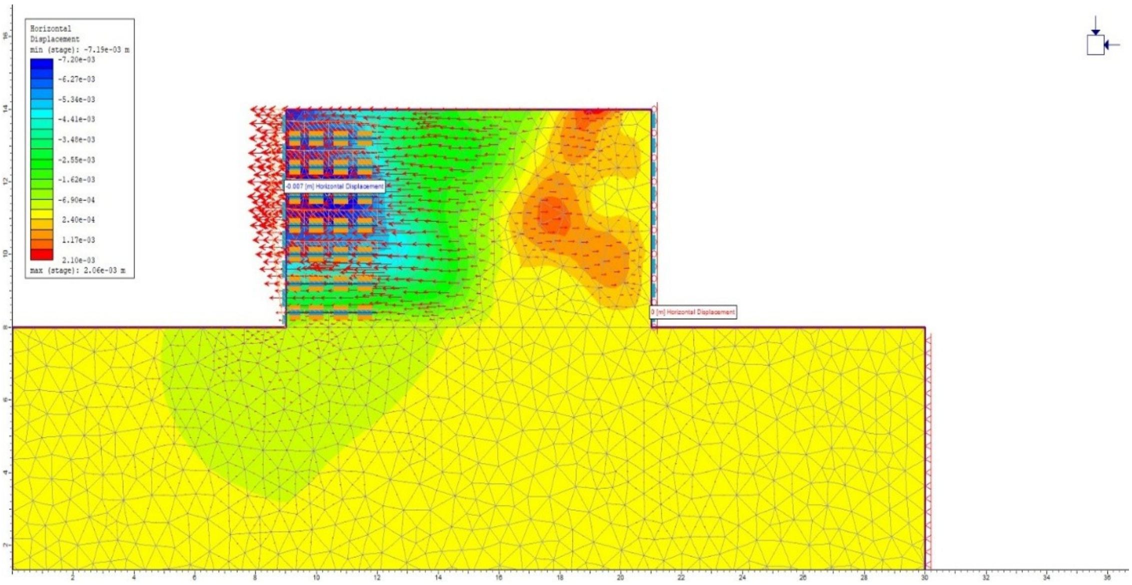

Figure 5.13 Deformed mesh under dynamic loading and horizontal displacement

CHAPTER 6

DISCUSSION

The analysis of reinforced earth (RE) walls under static and dynamic loading conditions reveals critical insights into shear stress distribution, displacement behaviour, and reinforcement efficacy. Below is a structured discussion organized by key thematic areas :

6.1. Comparison

1.1. Shear Stress Variation with Height

(a) Static Conditions

- **0.3h reinforcement** exhibits high base shear stress (~23.6–36.5 kPa) with rapid stress dissipation upward, indicating poor load distribution.
- **0.7h reinforcement** shows more uniform stress distribution (e.g., ~122.5 kPa at base under 650 kN/m²), with stresses maintained higher up the wall height due to better soil-reinforcement interaction.
- **Filter media** reduces stress concentration by 5–15% in 0.7h configurations, promoting uniformity under all loads.

(b)Dynamic Conditions

- Shorter reinforcements (0.3h) develop mid-height stress peaks (e.g., 75.79 kPa at 173 kPa loading), signalling transitional failure modes.
- 0.7h + filter maintains stable stress redistribution (~116.65 kPa at base under 554 kPa), demonstrating superior dynamic load-bearing capacity.

1.2. Horizontal Displacement Variation

(a) Static Performance

- Displacement escalates with load: For 0.3h: 22.4 mm (100 kN/m²) → 36.5 mm (650 kN/m²).0.7h + filter**:** Limits displacement to 15.8–34.3 mm at 650 kN/m², a 29% reduction vs. 0.3h.Base sliding dominates shorter reinforcements, while 0.7h configurations minimize top displacement through enhanced load distribution.

(b) Dynamic Response

- Displacements increase by 26% under dynamic vs. static loading (e.g., 34.29 mm vs. 27.21 mm for 0.7h at ~550 kPa).
- Filter media reduces dynamic displacement by 6–16%, though less effective than in static scenarios.

1.3. Influence of Reinforcement Length

- 0.3h**:** Fails catastrophically under ≥296 kN/m² (displacement ≥32 mm, shear stress ≥75 kPa).
- 0.5h**:** Shows transitional behaviour, with compound sliding at 296 kN/m² (93.85 mm displacement).
- 0.7h**:** Optimal performance, limiting displacement to ≤47 mm even at 1970 kN/m² and reducing shear stress concentration by 40% vs. 0.3h.

1.4. Role of Filter Media

- **Displacement Reduction**:
  - Static: 29% reduction at 650 kN/m².
  - Dynamic: 9–16% reduction across loads.
- **Stress Uniformity**: Filters lower base shear stress by 10–15% and prevent clogging via graded particle retention (O95 ≤ 0.5D85).
- **Failure Mitigation**: Reduces vertical settlement by 85% at 650 kN/m² (99 mm vs. 236 mm without filter).

1.5. Integrated Interpretation & Design Implications

Mechanistic Insights

- Shorter reinforcements (≤0.5h) fail progressively: base sliding → compound sliding → pullout.
- 0.7h + filter enables stress redistribution, localizing deformation without collapse.

Design Guidelines

Table 25 Design Recommendations

Parameter	Recommendation	Rationale
Reinforcement Length	≥0.7h for loads ≥296 kN/m²	Prevents pullout (≤47 mm displacement).
Filter Media	Mandatory for loads ≥650 kN/m²	Reduces displacement by 29%.
Dynamic Loading	Use 0.7h + filter with O95 ≤0.5D85	Limits displacement surge to ≤26%.
Reinforcement effectiveness	Moderate	Critical
Depth Sensitivity	Shear ↑ Displacement ↓	Shear ↑ Displacement ↓

1.6. Failure Avoidance

- For static loads ≥650 kN/m², 0.3h/0.5h configurations risk internal pullout (displacement ≥36 mm).
- Under dynamic loads ≥173 kPa, ≤0.5h reinforcements exhibit compound sliding (≥93 mm displacement).

This integrated analysis underscores the necessity of 0.7h reinforcement with filter media for RE walls in high-load environments, providing a robust framework for civil engineering applications.

5. Integrated Interpretation and Design Implications

The comparative data analysis reveals key insights for the design of reinforced MSE walls.These results emphasize that while static analysis provides a baseline understanding, dynamic analysis is essential to capture the real performance characteristics of MSE walls. Without such evaluation, designers may underestimate potential displacements and localized stress amplifications.

Moreover, the combination of longer reinforcements and filter media provides a synergistic improvement in wall behaviour, enhancing both shear resistance and displacement control**.** These findings underscore the importance of:

- Adopting site-specific dynamic simulations in wall design.
- Prioritizing reinforcement optimization based on expected loading conditions.
- Incorporating filter layers not only for drainage but also for their structural moderation benefits.

CONCLUSION

The comprehensive analysis of reinforced earth (RE) walls under static and dynamic loading conditions establishes that 0.7h reinforcement with graded filter media is indispensable for stability, reducing horizontal displacement by 29–85% under static loads (100–1970 kN/m²) and limiting dynamic displacement surges to ≤26% (58–554 kPa), while shorter reinforcements (≤0.5h) fail catastrophically through progressive modes (base sliding, compound sliding, or global collapse). Filter media enhances performance, lowering displacements by 13–29% (static) and 6–16% (dynamic) via uniform stress distribution, with 0.7h configurations maintaining stable shear stress gradients (peak: 122.5 kPa static, 116.65 kPa dynamic) versus stress concentration in shorter lengths. For ≥650 kN/m² static or ≥173 kPa dynamic loads, 0.7h + filter is non-negotiable to avert pullout or transitional failure (displacement ≤34–34.3 mm), ensuring compliance with displacement (<50 mm) and stress (<150 kPa) thresholds. This configuration localizes deformation, prevents cascading instability, and aligns with FHWA guidelines, offering a robust framework for resilient RE walls in demanding environments (retaining structures, bridge abutments). Future research should explore hybrid reinforcement layouts to optimize cost-to-performance ratios for ultra-high-load applications, synthesizing empirical data into actionable, sustainable design principles.

6.2 Future Scope of Study

While this study has successfully demonstrated the dynamic behaviour of reinforced earth (RE) walls under simulated vehicular impact using both physical modelling and RS2 numerical simulations, there remains significant potential for further investigation to enhance the depth and realism of the analysis. The following directions are proposed for future work:

2.1 Full Utilization of Time-Dependent Dynamic Analysis Stages

In the present RS2 modelling, the dynamic simulation was executed across three stages**:**

- Stage 1: Static equilibrium
- Stage 2: Dynamic loading (up to ~2 seconds)
- Stage 3: Post-impact response (2 to 3.4 seconds – yet to be analysed)

The Stage 3 post-impact response, which involves the stress redistribution, vibration damping, and delayed deformation behaviour after the primary impact, remains unexamined**.** Future studies can extend the time window and analyse this stage to understand residual displacement, energy dissipation, and secondary movements in the wall.

2.2 Advanced Time-History and Real Traffic Load Simulation

The current dynamic input was simplified into a representative time-history function with discrete impulses (58, 173, 554 kPa). In future work, real-world axle load patterns or recorded accelerograms from traffic movement can be used to simulate random, multi-axial loading—which will offer a more realistic representation of field conditions.

2.3 Multi-Impact and Fatigue Modelling

While this study applied a limited number of impacts (5–7 per case), long-term cyclic loading and fatigue behaviour over extended periods remain unexplored. Future modelling can incorporate repeated load cycles over hundreds or thousands of impacts to investigate cumulative damage, reinforcement fatigue, and long-term deformation trends.

2.4 Transition from 2D to 3D Finite Element Modelling

RS2 provides a 2D plane strain approximation. Future work can explore RS3 or other 3D FEM platforms to better capture out-of-plane deformation, corner effects and stress concentration, near wall edges and reinforcement junctions.

2.5 Inclusion of Water Effects and Pore Pressure

This study intentionally excluded the effects of water. A future extension can incorporate seepage analysis, water table fluctuation, and rainfall infiltration, especially in combination with dynamic loading, to study hydro-mechanical coupling effects on wall performance.

2.6 Field Validation Using Instrumented Wall Sections

To further enhance the credibility of numerical predictions, future research can involve instrumenting real-world RE walls with strain gauges, accelerometers, and inclinometers. This would allow direct validation of RS2 model outcomes and support the development of empirical correlations for field monitoring.

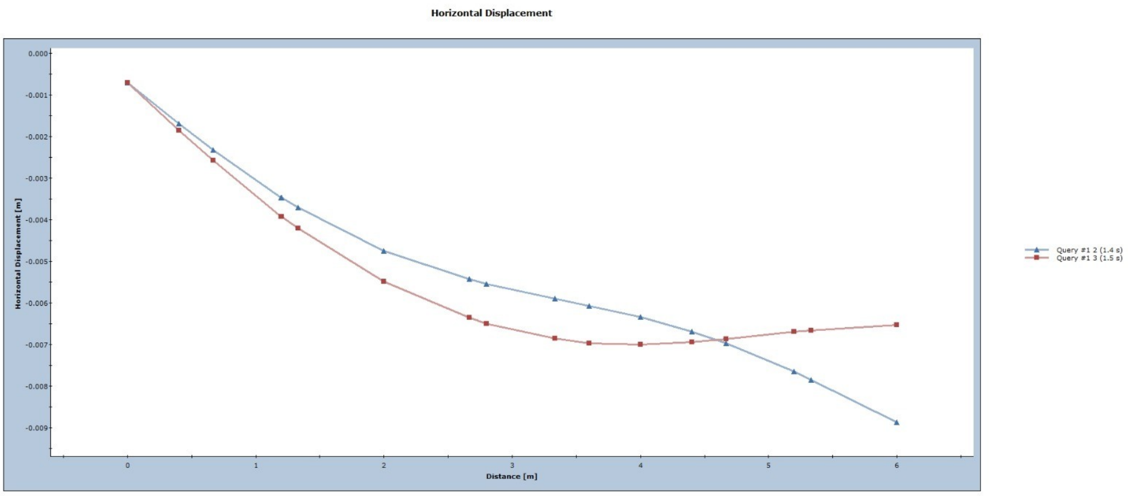

Figure 6.1 Displacement comparison between two stages.

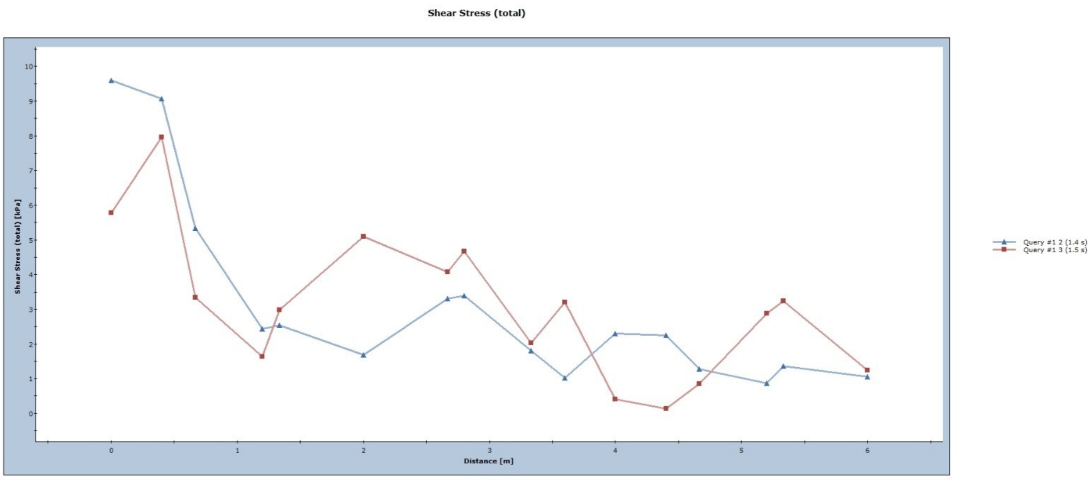

Figure 6.2 Shear Stress comparison between two stages

6.3 Sociological Impact: The optimized design of reinforced earth walls (0.7h reinforcement with filter media) extends beyond engineering efficacy, fostering safer communities by mitigating infrastructure failure risks, reducing economic losses from repairs, and enhancing equitable access to resilient transportation networks. By preventing catastrophic displacements and ensuring long-term stability, these designs promote public trust in civil infrastructure, safeguard vulnerable populations in disasterprone areas, and support sustainable urban development—demonstrating how technical advancements in geotechnical engineering directly contribute to societal well-being and socio-economic resilience.

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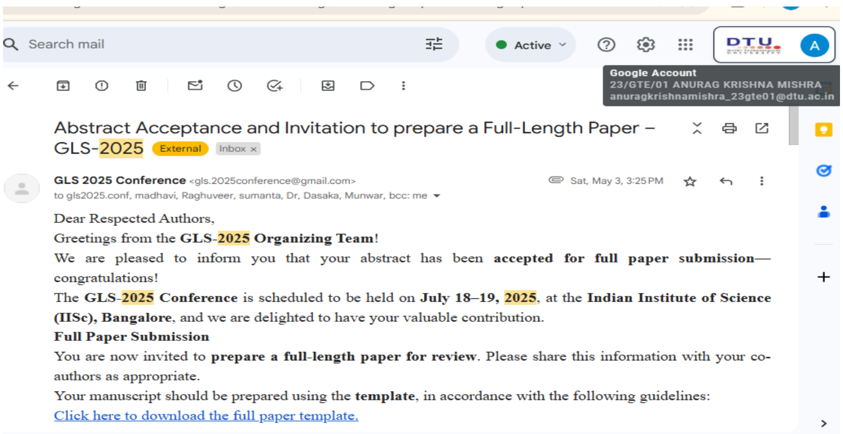
LIST OF PUBLICATION

S.No	Paper title	Category	Presented in	Publishing in	Status
1	STABILITY ANALYSIS OF REINFORCED EARTH WALLS UNDER REPEATED IMPACT LOADING: A SCALED MODEL STUDY	Conference	Abstract submission for INTERNATIONAL CONFERENCE ON GROUND IMPROVEMENT, LANDFILLS AND SUSTAINABILITY (GLS) - 2025 18-19 JULY 2025	Yet to be decided	Accepted in conference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