Dynamic behaviour of reinforced earth walls: A frequency-based investigation

N. V. Dasari, K. K. Gonavaram, H. Mudavath
National Institute of Technology Warangal, Warangal, Telangana, India,
dn22cer2r07@student.nitw.ac.in, kalyan@nitw.ac.in, mhl@nitw.ac.in

ABSTRACT: As urban development advances into seismically active territories, the design of retaining structures capable of reliably withstanding earthquake-induced forces necessitates the integration of material efficiency and sustainability considerations. In pursuit of this objective, A comprehensive experimental program utilizing 1g shaking table tests was conducted to elucidate the response characteristics of modular block faced geosynthetic-reinforced walls under variable seismic inputs. The investigation spans a range of seismic excitation frequencies ranging from 2.5 Hz to 10 Hz and intensities 0.1g and 0.5g to simulate realistic earthquake conditions. The research delineates the nonlinear response of reinforced systems under variable seismic demand. The experimental results reveal that the maximum acceleration amplification factor consistently occurs at the crest of the wall and increases under near-resonant conditions. By analysing the acceleration amplification patterns under varying excitation regimes, the study uncovers key soil structure interactions. These outcomes advocate for the incorporation of performance-based design frameworks for urban geotechnical systems, promoting infrastructure resilience against earthquake hazards. In alignment with the United Nations Sustainable Development Goals, this study contributes to the development of resilient and resource-efficient infrastructure systems.

1 INTRODUCTION

Reinforced earth retaining walls are flexible, economical and architecturally adaptable alternatives to traditional rigid gravity and cantilever walls. Since the early conceptualization of reinforcement by Vidal (1960), these concepts have evolved in to geotechnical and transportation infrastructure. To reduce construction duration, costs and user delays while enhancing safety, accelerated construction technologies including walls with precast facings are being adopted. However, an analysis of failed walls by Koerner et al. (2018) report that approximately 75% of failures in modular facings are attributed to poor design and construction oversight, of which 63% are associated with the use of fine-grained backfills and insufficient drainage leading to hydrostatic pressure buildup. Comparative experiments on segmental and wrap faced retaining systems were conducted by El-Emam and Bathurst (2005), in which models were subjected to progressively increasing Peak Ground Acceleration (PGA) applied in increments of 0.05 g at 3 Hz. The results showed that segmental walls could withstand nearly twice the critical acceleration of wrap faced walls before the onset of significant lateral displacement. Guler and Seek (2014) tested on reinforced walls which were exited using scaled El Centro earthquake at different PGA and observed that Acceleration Amplification Factor (AAF) increased with elevation along wall face. Extending reinforcement beyond potential failure surface effectively prevented instability of top facing blocks. Zheng et al. (2023) showed that modular block walls reached resonance at lower acceleration levels (0.25g) and developed bulging deformation with higher connection loads, whereas rigid faced reached critical state at 0.35g exhibiting sliding behaviour.

Existing design guidelines were primarily based on pseudo-static limit equilibrium concepts where reinforced soil mass is idealized as a rigid or quasi-rigid body and cannot explicitly account for influence of excitation frequency, shaking duration, cyclic degradation, progressive accumulation of deformations. Controlled physical modelling through shake table experiments offers a systematic and effective approach in examining fundamental response mechanisms under controlled loading conditions. In this study, tests are carried out on modular-block faced reinforced earth wall, focussing specifically on influence of excitation frequency and base acceleration on acceleration amplification, lateral deformation and reinforcement strain response.

2 EXPERIMENTAL PROGRAM

The experimental program evaluated the seismic response of reinforced earth retaining walls using 1-g shake table tests, with controlled material properties, reinforcement layout to ensure repeatability.

2.1 Materials

2.1.1 Backfill

Locally sourced river sand classified as poorly graded sand (SP) as per ASTMD 2487 (2017) having a specific gravity of 2.65 with negligible fines was utilized. The chosen sand was inert, free of organic matter and consistent, minimizing chemical and mechanical interactions with backfill and reinforcement.

2.1.2 Reinforcement

Uniaxial geogrid manufactured from high-tenacity polyester fibres with a tensile strength of 20 kN/m were adopted. The reinforcement length was maintained at 0.7 times the wall height (h) (Latha and Santhanakumar, 2015).

2.1.3 Facing.

Lightweight model scale facing units were fabricated in-house using M 25 grade self-compacting concrete. The blocks were designed with continuous shear key to ensure positive interlocking between adjacent units. The facing system primarily functioned as a construction aid and erosion protection measure.

2.2 Scaling Laws

Laboratory constraints hindered the accurate simulation of field-scale stress. Hence, mechanical equivalence is achieved through similitude principles established by Wood (2004). A scaling factor of 15 was adopted, representing a 10 m prototype height, while maintaining critical stress-strain dynamics within shaking table acceleration limits.

2.3 Construction and Instrumentation

To align model with prototype, a laminar container of dimensions 1 m x 0.6 m was used. Base was roughened with coarse sand for enhanced wave transmission. A 100 mm thick compacted sand was laid as foundation, followed by a levelling pad and then first modular block course. Pluviation technique was adopted to maintain uniform backfill relative density. Accurate construction was ensured through systematic layering, with facing blocks first, followed by backfill and reinforcement, with sensors embedded at specified depths. After reaching a height of 670 mm, surcharge load was applied in the form of mild steel plate, and formwork removed upon achieving equilibrium. The experimental framework utilized array of high sensitivity accelerometers, linear velocity displacement transducers, strain gauges as depicted in Figure 1 for precise measurement of dynamic responses.

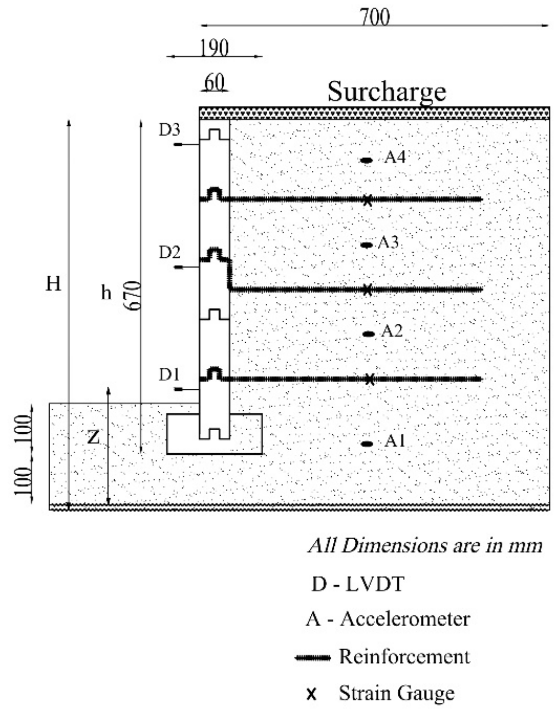

Figure 1. Schematic diagram of test setup.

2.4 Testing Sequence

The loading sequence involved uniaxial harmonic base motions. Being the model fundamental frequency equal to 11.65 Hz, loading frequencies of 2.5, 5.0, 7.5 and 10 Hz were selected to avoid resonance. PGA increased from 0.1g to 0.5g in 0.1g steps (A1-A5), with each PGA consisting of 30 cycles, including a ramp-up and ramp-down to prevent sudden shocks. A representative input acceleration time history corresponding to 5 Hz excitation is shown in Figure 2.

3 SEISMIC RESPONSE

3.1 Acceleration response

At every excitation, the AAF varies non-linearly along height as depicted in Figure 3. To enable a comparative assessment across diverse experimental parameters, normalized elevation is adopted which is measure of elevation excluding foundation layer (z) to total height of model (H) as in Figure 1. At lower frequencies, AAF initially increased with PGA and decreased when model reached plastic state.

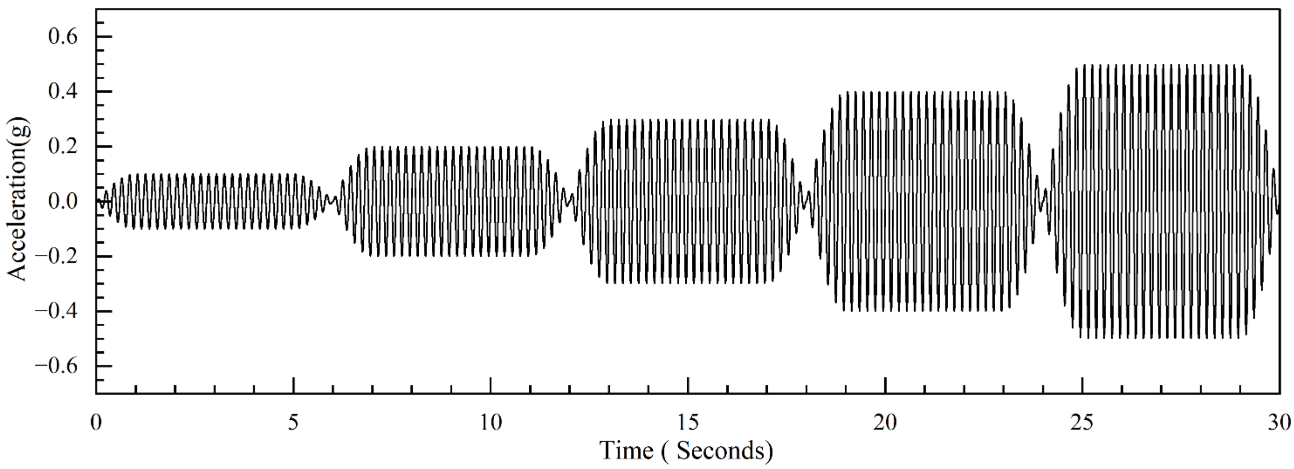

Figure 2. Input motion

At 2.5 Hz, the model reached plastic state at 0.4g and therefore testing at 0.5g was terminated. At a frequency of 5 Hz, the AAF increased significantly by 27%, on increase in PGA from 0.1 g to 0.2 g. This was followed by smaller increases of 4.5% on reaching 0.3 g and an additional 0.6% increase to 0.4g. These changes indicate a gradual degradation of stiffness and an impending yielding. Beyond this point, the AAF decreased by approximately 8%. However, at 10 Hz, which is close to the fundamental frequency of the system, a pronounced amplification of 2.59 was observed at 0.1g. This was followed by a gradual reduction with increasing PGA. The underlying mechanism of nonlinear soil response at increasing acceleration induces larger shear strains, which increase damping and reduce shear modulus, thereby supressing amplification beyond a critical acceleration (Huang et al., 2011).

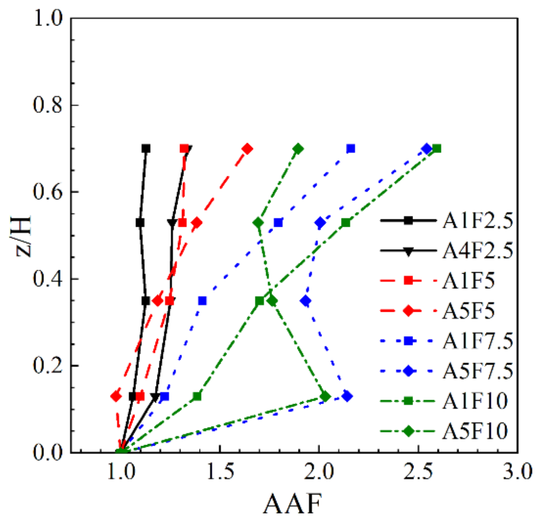

Figure 3. AAF along elevation of model

3.2 Displacement Response

A notable positive relationship is evident between settlement and lateral displacement, suggesting that increased vertical loads on the backfill contribute to outward movement of the wall. The reinforced region near facing experienced reduced settlement, whereas unreinforced region farther from facing exhibited greater settlements. Relatively lower displacements are observed at toe due to basal restraint, while substantial bulging deformations are seen in mid and upper sections as shown in Figure 4, due to flexibility of modular block facing, offering benefits over rigid facing. To categorize seismic damage grades and overall performance, the displacement-based damage criteria proposed by Li et al. (2021) were utilized.

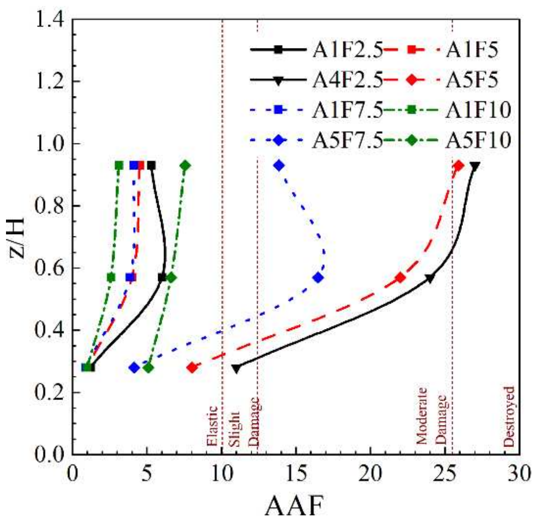

Figure 4. Lateral displacements along facing

The model reached plastic state at 0.4g under 2.5 Hz excitation, where the lateral displacement approached about 4% of model wall height (h). At lower frequencies, bulging type deformation is observed, whereas sliding response is observed at higher frequencies, albeit with generally low residual displacement. At peak frequency of 10 Hz, the wall predominantly. stays in an elastic condition up to 0.4g, with minimal residual displacements up to 6.74 mm. For an intermediate PGA of 0.3 g, an increase in frequency from 2.5 Hz to 5 Hz, 7.5 Hz, and 10 Hz resulted in a notable decrease in residual lateral displacement by 18.4%, 43.9% and 10.78%, respectively, highlighting the stabilizing effect that higher-frequency excitations have on the accumulation of permanent deformations.

3.3 Strain Response

The results show that reinforcement strain increases systematically with increasing base acceleration, indicating progressive mobilization of tensile forces as shaking intensity increases. In this study, the basal reinforcement layer consistently exhibited the highest tensile strain, corroborating several experimental investigations. This behaviour can be attributed to the elevated overburden pressure and surcharge sustained by the lower layers, leading to enhanced mobilization of reinforcement tension. The residual strain in the bottom layer reached about 0.5% at 0.4 g for 2.5 Hz excitation as represented in Figure 5. A similar level was noted at 7.5 Hz at 0.5g, indicating frequency significantly affects material response to dynamic loading. At 5 Hz, the residual strain increased to about 0.94% at 0.5g, whereas at 10 Hz the cumulative residual strain remained very small (approximately 0.17%) even after the full loading sequence.

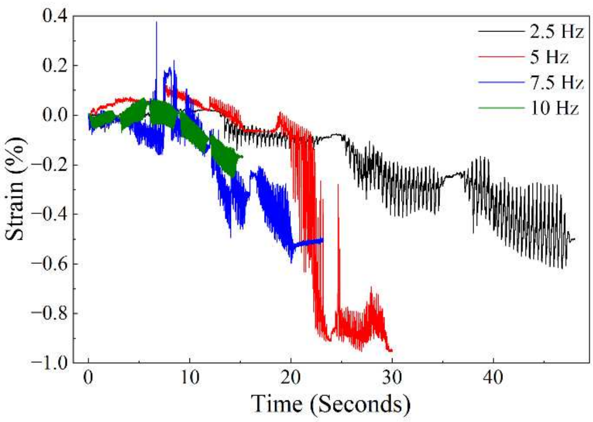

Figure 5. Strain response of lower-level reinforcement at different excitation frequencies

The observed strain evolution exhibits a strong correlation with wall deformation. Furthermore, Tatsuoka (1993) indicated that relatively stiff facing systems enhance soil confinement and diminish reinforcement strains, thereby mitigating tensile load mobilization. The current findings validate these mechanisms and illustrate that strain development is governed by both deformation demands and stress redistribution within the reinforced soil matrix.

4 CONCLUSION

- Excitation frequency is crucial in determining the seismic performance of reinforced earth walls. Lower frequency motions result in larger permanent deformations and an earlier onset of plasticity, even when the peak accelerations are similar.
- High levels of acceleration amplification observed near resonance do not necessarily corelate with increase in structural damage, as response is mainly elastic and the deformation remains largely recoverable.
- The buildup of permanent lateral displacement is primarily controlled by frequency-dependent soil nonlinearity and the progressive accumulation of strain in the backfill.

This study emphasizes the need for deformation-based performance criteria in seismic design. These insights promote performance-based design frameworks. Such approaches enhance infrastructure reliability and failure predictability.

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