# SEISMIC LOADING AND REINFORCEMENT EFFECTS ON THE DYNAMIC BEHAVIOR OF SOIL SLOPES

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***Resume***

Despite the significant research on the seismic stability of earth structures, critical gaps remain in understanding the dynamic response of soil slopes with varying reinforcements. These gaps were addressed in this study by using a small shake table to investigate the dynamic behavior of soil slopes under different conditions. The research examines responses at various frequencies, the effect of reinforcement methods, and the impact of slope height. Results indicate that the higher frequencies and amplitudes lead to increased displacements, while reinforcement reduces crest displacement by 21 to 45%. Steeper slopes (35° and 40°) also show increased displacements by 9 to 65%, compared to a 30° slope. The importance of reinforcement in improving the seismic resilience of soil slopes is highlighted in this study, offering practical insights for engineering design.

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## 1 Introduction

The slope stability analysis is a critical aspect of geotechnical engineering that is pivotal in ensuring the safety and longevity of civil engineering structures built on or adjacent to sloping terrain [1]. The stability of slopes is influenced by a myriad of factors, including geological and geotechnical conditions, external loads, and environmental factors. In this study, we delve into the intricate realm of slope stability analysis, focusing on comparing reinforced and unreinforced materials [2]. Slopes are ubiquitous in natural and engineered landscapes, presenting challenges that demand a comprehensive understanding of their behavior and the potential risks associated with instability [3]. Unstable slopes can lead to disastrous consequences, including landslides, erosion, and structural failures. Therefore, a thorough investigation into the slope stability is essential for designing resilient and safe structures in hilly and mountainous regions [4].

Reinforcement techniques have emerged as a proactive and innovative approach to enhance the slope stability [5]. Introducing various reinforcement materials, such as geosynthetics, geogrids, and soil nails, has opened new avenues for mitigating the slope instability and improving overall slope performance [6]. This study aim was contribute to the existing body of knowledge by evaluating and comparing the effectiveness of reinforced and unreinforced materials in slope stability analysis. The investigation involves a comprehensive review of relevant literature, case studies, and advanced analytical methods to assess the performance of slopes under different conditions. By considering both laboratory experiments and real-world applications, this study aim was to provide valuable insights into the mechanisms governing slope stability and the role of reinforcement in enhancing the overall resilience of slopes [7]. As societies continue to expand into diverse topographies, understanding the complexities of slope stability becomes increasingly crucial for sustainable and safe development [8]. The findings of this study are anticipated to contribute to the optimization of slope design practices, thereby fostering the development of robust infrastructure in areas prone to slope instability. The main objectives of this work are as follows:

- The dynamic response of soil slopes is investigated across different frequencies, aiming to understand how varying frequencies affect the slope stability under seismic conditions.

- The influence of reinforcement on soil slope behavior is analyzed, focusing on how various reinforcement techniques alter their dynamic performance.
- The effects of different amplitude levels on the dynamic response of soil slopes are examined, assessing the impact of amplitude changes on displacement and stability during seismic events.

## 2 Literature survey

Shinoda and Miyata [9] stated in geotechnical engineering, slope stability analysis is a challenging task because of the multimodal function optimization issue. Though its parameters for both unreinforced and reinforced soil slopes have not been fully explored, particle swarm optimization (PSO) is a highly effective technique for finding critical slip surfaces. The study computes safety factors by taking into account force and moment equilibriums, which include reinforcement tensile force. It was discovered that the PSO's computing efficiency increased the maximum number of slip surface nodes, and research was done on how sensitive PSO parameters were to safety factor variations.

Keskin and Kezer [10] examined slope stability in municipal solid waste (MSW) landfills using finite element and limit equilibrium methods. They discovered that employing geogrid materials can considerably improve the stability of landfill slopes. When the best geogrid settings are applied, the slope's safety factor can be raised by up to double. Geogrid- reinforced slopes can become steeper, allowing for additional solid waste storage. Given the high initial investment cost of MSW landfills, storing more solid waste with geogrids can result in large economic gains. The study offers optimal geogrid values for maximum reinforcing effects in MSW landfill slopes.

Jyothi and Krishna [11] focused on enhancing the slope stability of embankments built with locally accessible materials as a result of fast industrialization and urbanization. The authors proposed that geotechnical engineers can strengthen these embankments by using geogrid reinforcement with native soil or by replacing the soil with pond ash. The study looks at a road embankment with a crest width of 8 m, side slopes of 2H:1V, and a height of 5 m resting on 10 m thick c-/soil. The Mohr-Coulomb material and Morgenstern-Price approach are used to model the soils and compute the factor of safety (FoS) for a critical slip surface. The best arrangement of geogrids in the first and fourth layers in conjunction with the pond ash fill embankment results in a greater factor of safety of 2.928.

Arvin et al. [12] used the strength reduction technique (SRM) to study the three-dimensional stability of slopes reinforced with geocells. The research takes into account the surrounding soils, as well as the geocells and their filling. The slope stability parameters, such as geocell placement, multilayer reinforcement pattern, and geocell layer number, are assessed using ABAQUS to calculate FoS. Through the 3D-SRM slope stability analysis, the SRM procedure's dependability is confirmed.

Collin et al. [13] examined Yeager Airport's reinforced slope failure in 2015 at Charleston, West Virginia. Strength parameters, slope geometry, and soil reinforcement configuration are assessed using inverse limit-equilibrium and permanent deformation studies. Whereas finite-difference permanent deformation studies comprehend internal stresses and deformations of the reinforced soil slope, three-dimensional limit-equilibrium calculations concentrate on the direction of uniaxial geogrid reinforcement. The findings support field observations made after the breakdown and emphasize the value of carrying out several types of analysis in complex slope failures.

Patil et al, [14] examined the behaviour of model footings' bearing capacities on slopes of reinforced embankments constructed from pozzolanic waste materials, such as ground granulated blast furnace slag (GGBFS) and fly ash. It looks at how well rubber grid and geogrid, two forms of reinforcement, work to increase load carrying capability. That study took into account the position, embedment depth, and slope angle of reinforcement. The load carrying capacity is found to decrease with slope angle and edge distance, with a 1.2 embedment depth ratio being the ideal value. Rubber grid reinforcement outperforms geogrid reinforcement; the study highlights the efficient use of leftover Pozzolanic materials.

Amena [15] investigated the durability of clay soil filled embankments with plastic garbage. Utilizing PLAXIS 2D geotechnical software, the author examined stability in a range of scenarios, taking into account factors including embankment shape, material properties, and reinforcement strength. The findings indicate that the factor of safety falls with slope height and angle but rises with geogrid axial strength above 500 kN/m. The study conclusion is that embankment fill can be made from clay treated with plastic garbage.

Qiu et al. [16], looked into the failure modes and dynamic response patterns of concrete gravity dams exposed to powerful earthquakes. A reliable technique for investigating the failure modes and dynamic properties of these structures is dynamic shaking table testing. Using a gravity dam model on a shaking table, the research integrates different dynamic loads and looks at how damage develops. The findings offer guidance for gravity dam shaking table studies, the determination of structural dynamic characteristic parameters, and the validation of damage diagnosis techniques.

Wang et al. [17], investigated the impact of geohazards, such as earthquakes and heavy rains, on regional stability is examined in this study. It solves safety factors for slopes associated with rainfall and earthquakes using a three-dimensional slope dynamic model and a rigorous analysis technique. The findings indicate that saturation and permeability coefficient have a relatively minor influence on safety factors during rainfall, however, porosity has a larger effect. The authors found that when both horizontal and vertical seismic effects are taken into account, slope stability is reduced.

Beyene et al. [18], developed a construction with four walls joined by three slabs without coupling beams and showed strong coupling in a study on the interaction between slabs and reinforced concrete walls on a shaking table. Walls may collapse due to this unanticipated reaction mechanism, as demonstrated by previous earthquakes. The effective width (EW) of the slabs was shown to have a substantial impact on the response, raising the structure's overall stiffness and strength ratio. Longitudinal reinforcement buckling resulted from twofold maximum shear stresses and increased compression axial forces due to the increased BS and redistribution of demand among wall piers.

Hore et al. [19], used a shaking table to investigate the dynamic behavior of a wrap-around sand embankment. Sand beds with varying relative densities were prepared using a mobile, portable pluviator. In a Plexiglas container, a 408 mm-tall wrap-faced retaining wall model was built using a prototype to model a scale factor of N = 10. The percentages of Sylhet sand that were utilized were 48%, 64%, and 80%. Three distinct surcharge pressures and sinusoidal peak input motions were used in the tests. The amplification of acceleration was found to be proportional to the base acceleration and inversely related to the surcharge load. Face displacement rose with base acceleration and reduced with rising surcharge pressure.

The literature on slope stability analysis reveals a range of methods, such as particle swarm optimization (PSO) and finite element analysis, to identify the critical slip surfaces and optimize reinforcement configurations, essential for assessing slope behaviour under seismic conditions. While these studies demonstrate the effectiveness of geogrid and geocell reinforcements in improving stability, they often focus on static or simplified dynamic conditions, leaving gaps in understanding the full dynamic response of slopes during seismic events. Additionally, dynamic shaking table tests have provided insights into failure modes, yet they often lack comprehensive exploration of the interplay between seismic loading, slope reinforcement, and material properties. The problem lies in the limited experiment on the dynamic response of reinforced and unreinforced soil slopes under varied seismic conditions. This gap motivated our research, which aimed to use shaking table experiments to provide a deeper understanding of slope stability under seismic loading, focusing on the real-time dynamic behaviour of different slope configurations.

## 3 Research methodology

In this section, the process of creating a compact shake table for experimentation is delved into, with several crucial steps outlined. Initially, emphasis was placed on developing a model of a soil slope, wherein the specific soil type is carefully identified. This step is pivotal in ensuring the precision and applicability of the subsequent experiments. Following this, the focus shifts towards determining the optimal settings for acceleration and frequency on the shake table. These parameters are instrumental in replicating authentic seismic scenarios. Subsequently, attention turns to comprehending how the soil slope responds under diverse conditions. The approach involves subjecting the model to varying combinations of acceleration and frequency, accurately observing and recording the ensuing soil reactions. The data obtained from these experiments furnishes valuable insights into the dynamic behaviour of the soil slope, forming a solid foundation for subsequent analysis and interpretation. This systematic methodology establishes the framework for making meaningful contributions to understanding of soil behaviour in the face of seismic conditions.

### 3.1 Testing equipment and material

In this research, a scale factor of 1/10 $(\lambda = L_F/L_M = 10)$ was applied to create physical models, where $L_F$ represents the full-scale prototype dimension, and $L_M$ the model dimension. The geometric scale factor influences all dimensions, including length, height, and width, ensuring the physical model is a scaled-down representation of real-world soil slopes. Dynamic similarity was achieved using Froude scaling laws, which maintain similarity between the model and prototype by accounting for the effects of gravity [20]. This ensures that the dynamic response observed in the model correctly represents the behaviour at full scale. For instance, displacement scales with $\lambda$, velocities scale with $\lambda^{1/2}$, and accelerations remain the same across the model and prototype. As a result, the forces acting on the model, such as gravitational and inertial forces, were correctly scaled to maintain the accuracy of dynamic responses under the seismic loading.

To replicate the physical characteristics of full-scale soil and reinforcement materials, material properties were scaled by the geometric scale factor. The mass density of the model soil was adjusted to maintain similarity in inertial forces, with the stress-strain behavior of the materials scaled by $\lambda$. Specifically, the material density was scaled by $\lambda^0$ (constant), while the applied forces were scaled by $\lambda^3$ to account for the difference in model volume. These adjustments ensured that the mechanical behavior of both soil and reinforcement in the model mimicked that of the full-scale prototype, accounting for the significant contributions of both inertia and gravitational forces. By addressing these scaling principles, the physical model provides reliable insights into the dynamic behavior of soil slopes under the seismic conditions. The integration of geometric, dynamic, and material property scaling ensures that the results are transferable to the real-world applications, offering valuable implications for improving the seismic resilience of full-scale soil slopes.

### 3.1.1 Shake table

A shake table, sometimes referred to as a seismic simulator, is an advanced apparatus intended to mimic the intricate and frequently intense movements of the Earth's crust during an earthquake [20]. The shake table, which consists of a robust platform backed by a network of hydraulic or mechanical actuators, can imitate a variety of ground motions, enabling engineers and researchers to examine how buildings, bridges, and other infrastructure behave structurally during an earthquake [21]. The table's capacity to replicate various seismic activity levels and frequencies offers important insights into the structural resilience of buildings and aids in the creation of earthquake-resistant designs. By carefully adjusting the infrastructures table's movements, researchers may apply the dynamic stresses encountered during an earthquake to models or real structures [22]. The ability to test and improve seismic-resistant building materials and methods in a controlled setting advances earthquake engineering and improves our capacity to reduce the destructive effects of seismic occurrences on the built environment.

The experimental investigations were conducted using a state-of-the-art unidirectional shake table, as depicted in Figure 1. The shake table boasts a substantial-top surface area measuring 1.5 x 1.5 m, providing ample space for testing and analysis. With an impressive maximum load-carrying capacity of 2000 kg, the shake table is well-equipped to handle a diverse range of experimental setups.

This advanced apparatus offers remarkable control over testing parameters. The maximum theoretical frequency achievable on the shake table is 10 Hz, ensuring the simulation of a wide spectrum of dynamic conditions. Additionally, the shake table is capable of achieving a maximum displacement of ±50 mm, allowing for precise and controlled movements that replicate the real-world scenarios with a high degree of accuracy.

The robust specifications of the shake table make it an ideal platform for conducting experiments that require a combination of strength, precision, and versatility. This state-of-the- art equipment played a pivotal role in ensuring the reliability and comprehensiveness of the experimental data collected for the study.

### 3.1.2 Soil container

The experimental setup employed a rigid-type container with internal dimensions measuring 1.0 m x 1.0 m x 1.0 m. This container was securely affixed to a shake table to simulate dynamic movements. Crafted from sturdy Perspex glass with an 18 mm thickness, the container's structural integrity was further enhanced by incorporating flat and angle structural steel sections, as illustrated in Figure 1(a). To augment its shock-absorbing capabilities, Expanded Polyethylene (EPE) foam was strategically applied along the inner boundary of the container, oriented perpendicular to the anticipated direction of the shake table's movement [23]. This not only served to protect the contents, but added an extra layer of insulation against potential impact forces, as well.

Furthermore, the base of the container underwent a surface modification process to induce roughness. Industrial adhesives were employed to securely adhere sand particles to the base, creating a textured surface [24].

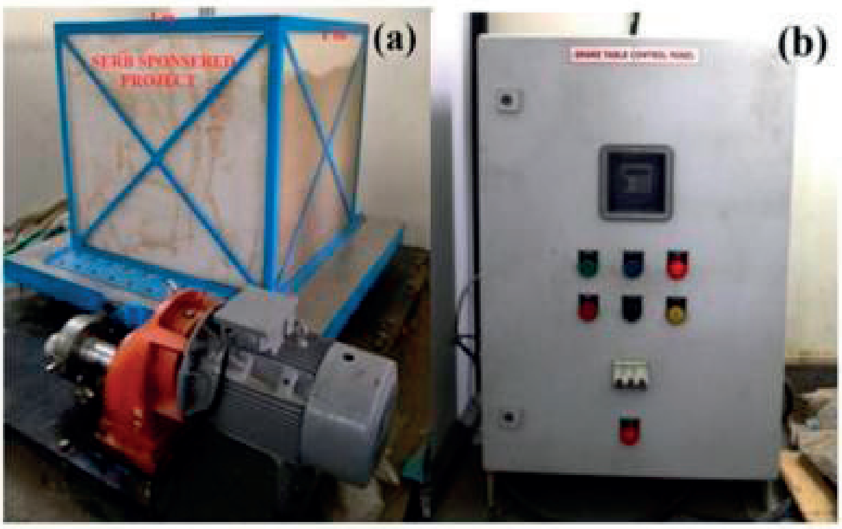



***Figure 1*** *(a) shake table and (b) control panel*

This deliberate roughness is instrumental in simulating real- world scenarios and introduces an additional layer of complexity to the experimental conditions. The construction and thoughtful enhancements of the container contribute to the precision and reliability of the experimental setup, ensuring accurate and meaningful results.

### 3.1.3 Absorbing boundary

The efficacy of a soil container's design in influencing the dynamic response of soil cannot be overstated, as improperly designed artificial boundaries can significantly impact the overall behaviour of the soil [25-26]. To mitigate undesirable effects, it is advisable to incorporate absorbing materials along the boundaries. In our current experimentation, commercially available EPE foam panels were chosen for utilization as absorbing boundaries.

In the experimental setup, these EPE foam panels were strategically positioned on both inner sides of the end walls, arranged perpendicular to the direction of shaking. This deliberate placement was aimed at minimizing any adverse boundary effects on the dynamic response of the soil. In this we maintained a foam thickness of 25 mm. This careful adherence to established principles ensured that our experimental conditions align with recognized standards, promoting reliable and meaningful results in the study of soil dynamics.

## 3.2 Material properties

Two distinct types of materials were employed as fill material in the project specifically, fine sand and coarse sand [27]. The reinforcement material chosen for this application is Geonet [28], characterized by an impressive axial strength of 50 kN/m, as illustrated in Figure 2. This strategic combination of fine and coarse sand, coupled with the robust axial strength of the Geonet, underscores a fine approach to optimizing the structural integrity of the project. To prepare the slope model fine sand and coarse sand are mixed in the proportion of 80:20; see Figure 2(a) of mixed soil. The shear strength [29] parameters (cohesion and friction) were determined by direct shear test. Table 1 illustrates the properties of mixed soil.

## 3.3 Preparation of reinforced slope

The preparation methodology for reinforced soil slopes closely mirrors that of their unreinforced counterparts. In both cases, careful attention is paid to key engineering principles. However, the integration of reinforcement introduces an additional layer of complexity and structural support. In the context of reinforced soil slopes, a pivotal element in the process involves the incorporation of a Geonet with a significant tensile strength of 50 kN/m. The Geonet, placed at 100 mm intervals, is utilized as a robust reinforcement mechanism, enhancing the slope's overall stability and strength. To prepare the slope surface the desired slope angle was marked on the soil container. The soil slope models were constructed in the container by the controlled volume method. The slope surface was initially supported by a wooden plank and then removed after preparation of the finished slope.

This study was also focused on replicating the relative spacing and interaction effects of reinforcement layers within the confines of our scaled model. The 100 mm interval was selected based on scaled-down dimensions that maintain similarity in dynamic experiments, adhering to geometric scaling laws and practical considerations in physical modeling. This

***Table 1*** *Properties of mixed soil*

| Type of Soil | Mixed soil |
|---|---|
| Density of soil (kN/m3) | 17 kN/m3 |
| Cohesion (kN/m2) | 0 |
| The angle of internal friction ( $\varphi$ ) | 40° |
| Specific gravity (G) | 2.7 |
| Maximum void ratio | 0.66 |
| Minimum void ratio | 0.54 |
| Relative density | 83.33% |

*(a)* *(b)*

***Figure 2*** *Material used (a) mixed soil of fine sand and coarse sand, (b) Geonet* interval was deemed appropriate to capture significant interactions between the geogrid and soil in a controlled laboratory environment, facilitating the observation of dynamic responses under seismic loading conditions. Moreover, the research was aimed to provide insights into the dynamic behavior of reinforced soil slopes rather than precisely replicating every aspect of full- scale field conditions, which may involve variable terrain and construction practices. The chosen interval allowed to study the effectiveness of geogrid reinforcement in enhancing slope stability and strength under controlled seismic loading, contributing valuable data to the understanding and improvement of soil slope design practices.

By interspersing the Geonet at regular intervals, the slope gains a reinforced structure capable of withstanding greater loads and environmental pressures. This deliberate placement ensures a uniform distribution of reinforcement, minimizing the risk of localized weaknesses. The axial stiffness of 50 kN/m plays a crucial role in providing the necessary tensile strength to the soil, preventing excessive deformation and potential failure. This methodical approach to reinforced soil slope preparation not only aligns with established engineering practices for unreinforced slopes but introduces the strategic reinforcement element, as well. which significantly enhances the slope's overall resilience and longevity. The accurate placement of the Geonet reinforces the stability of the slope, offering a robust solution that stands up to the challenges posed by various environmental factors.

## 4 Result and discussion

In this research on the dynamic response of soil slopes under seismic loading conditions using scaled physical modelling, the comment regarding boundary conditions pertains to ensuring their accurate definition and assessment. Boundary conditions in this study encompassed several critical factors aimed at replicating real-world scenarios. These included setting the precise foundation conditions to replicate the soil bed characteristics encountered in the field, ensuring lateral constraints on the model slopes to simulate natural slope boundaries, and applying dynamic loading parameters that mirror seismic events of interest. The various frequencies were set on the control panel as shown in Figure 3. The vertical crest displacement was measured with a digital planimeter. The sinusoidal force was induced by changing the frequencies and amplitudes. The duration of each force was applied for 10 cycles of the shake table.

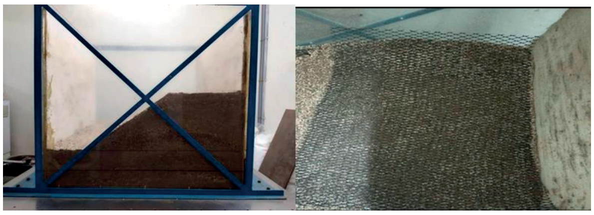
Furthermore, it is acknowledged that the precise calibration and validation of these boundary conditions were essential to ensure the reliability and relevance of our experimental outcomes. This calibration process involved rigorous testing and adjustment of model parameters to match the established benchmarks and theoretical predictions, thereby enhancing the accuracy and applicability of our findings. By addressing these aspects, this research was aimed to minimize biases and uncertainties associated with boundary conditions, thereby strengthening the scientific rigor and validity of our investigations into soil slope dynamics under seismic loading conditions. To ensure homogeneity in the built models for shake table tests under seismic loading, we controlled the material consistency, layering, compaction, model geometry, and boundary conditions. All the models were constructed using the same soil type, uniformly mixed, and compacted to consistent densities and moisture contents, ensuring identical mechanical properties. Sensor placements were standardized across models, and seismic loading was precisely replicated in each test. These measures were rigorously applied and monitored to eliminate variability, ensuring that any observed differences in the dynamic response were due to the seismic loading rather than inconsistencies in model construction. This approach was critical for the reliability and repeatability of the experimental results.

### 4.1 Shaking table setup

Shaking table tests on model slopes serve as a crucial method for examining how the slopes respond to dynamic loading conditions, specifically assessing their behaviour in relation to base shaking frequency and shake table amplitude. In this study, a slope angle of 30°, 35° and 40° has been adopted for all models to provide a consistent basis for observation and analysis. The slope fill comprises dry soil composed of both fine sand and coarse sand, carefully tamped to attain optimal compaction levels. The height of the slopes is consistently maintained at 300 mm across all tests, ensuring a standardized parameter for evaluating the dynamic response.

Figure 4 presents the completed slopes of the models, showing the physical manifestation of the constructed slopes. Meanwhile, Figure 5 presents a schematic diagram illustrating the intricate details of the soil slope model, offering a comprehensive visualization of the experimental setup. To explore the dynamic response further, the slope models undergo testing at


***Figure 3*** *Data acquisition method*



(a) (b)

***Figure 4*** *(a)Finished slope model (b) Placing of geonet*

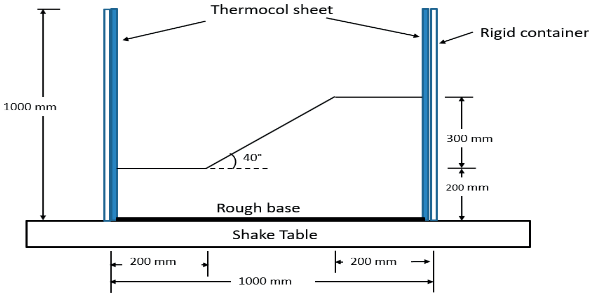



***Figure 5*** *Schematic diagram of soil the slope model*

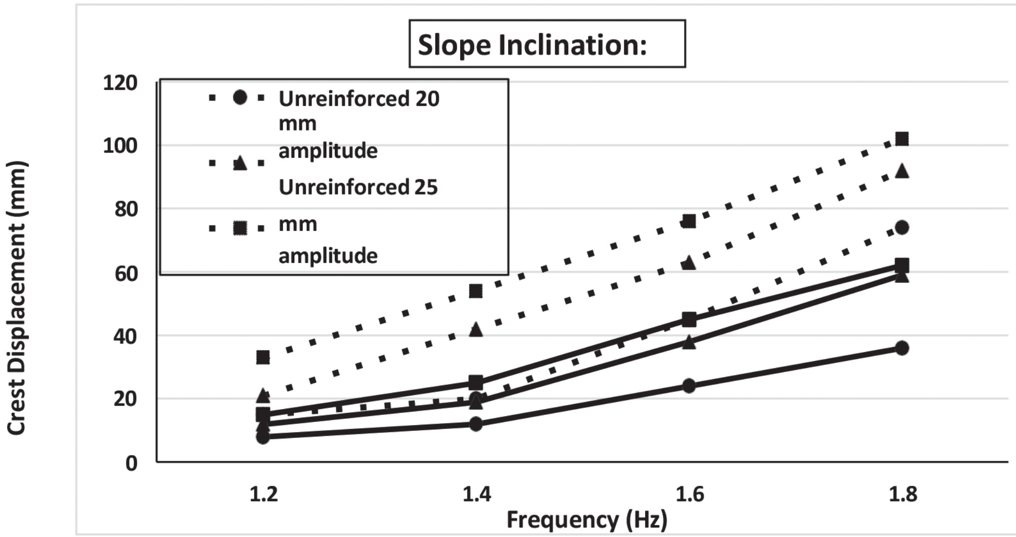



***Figure 6*** *Effect of frequency and amplitude on 30° unreinforced and reinforced soil slope model*

frequencies of 1.2,1.4, 1.6, and 1.8 hertz, encompassing a spectrum of loading conditions. Varied amplitudes of 20, 25, and 30 mm are applied during the tests, enabling a comprehensive examination of the slope behaviour under different dynamic parameters. This meticulous testing protocol allows for a nuanced understanding of how the slopes interact with varying frequencies and amplitudes, contributing valuable insights into the field of slope stability and earthquake engineering.

The shake table tests involved subjecting slope models to varying frequencies and amplitudes, with subsequent recording of crest settlements, as detailed in following Figures 6-11. Notably, the analysis reveals a consistent occurrence of bulging at the toe of each slope model, indicating a common pattern of deformation under the applied seismic conditions.

### 4.2 Experimental results of soil slope model without reinforcement

Figures 6-11 provided below present the empirical findings derived from a soil slope model with a height of 300 mm, encompassing diverse slope inclinations. These results offer a comprehensive overview of the performance and behaviour of the soil under varying slope conditions.

Figure 6, outlines the outcomes of an unreinforced and reinforced soil slope model subjected to varying frequencies, amplitudes, and corresponding measurements at a 30° slope inclination. Figure 6 shows that as frequency increases, the crest displacement rises. In addition, it indicates that with the increase of amplitudes from 20 mm to 30 mm, the crest displacement increases. This data serves as valuable information for understanding the dynamic behavior of the unreinforced soil slope under different loading conditions, offering crucial insights for geotechnical and structural analyses.

In the first trial at a frequency of 1.2 Hz, the crest displacement increases from 8 mm to 15 mm, as the amplitude rises from 20 to 30 mm for the reinforced soil slope model. This suggests that the higher amplitudes at this frequency result in an increased deformation of the reinforced soil slope. A similar trend is observed in subsequent trials at frequencies of 1.4, 1.6, and 1.8 Hz. Notably, as the frequency increases, there is a tendency for crest displacement to increase for the same amplitude. After a comparison of unreinforced and reinforced soil slope model, it is observed that there is a considerable reduction in the slope deformation. At a frequency of 1.2 Hz, the crest displacement is decreased from 15 mm to 8 mm, for an amplitude of 20 mm. A similar trend is observed for 25 mm and 30 mm amplitudes and for subsequent increase in frequency from 1.4 to 1.8 Hz.

While acknowledging that the higher magnitude seismic events may have higher frequency components, this study's focus on frequencies between 1.2 to 1.8 Hertz was aimed at capturing a realistic spectrum of seismic loading conditions relevant to the scaled physical model and providing insights into the dynamic response of soil slopes under controlled experimental settings. This information is valuable for understanding the stability and performance of the reinforced slope under different loading conditions, aiding in geotechnical engineering assessments and slope stability analyses. The reinforced nature of the slope suggests potential improvements in stability compared to unreinforced slopes, as indicated by the trends observed in the crest displacements.

Figure 7 summarizes the results obtained from testing an unreinforced and reinforced soil slope model inclined at 35° under different frequencies. In the first trial of an unreinforced slope model at a frequency of 1.2 Hz, as the amplitude increases from 20 to 30 mm, there is a corresponding rise in crest displacement from 18 to 36 mm. This suggests that the higher amplitudes

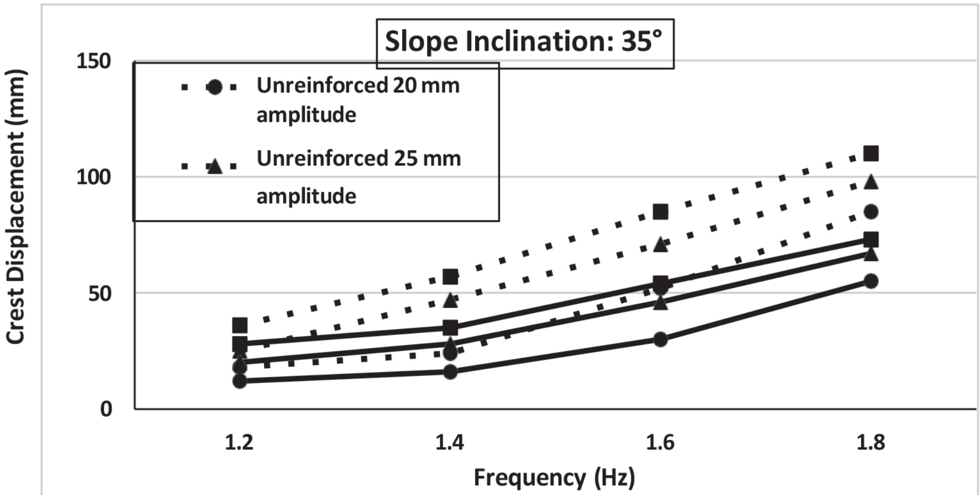



***Figure 7*** *Effect of frequency and amplitude on 35° unreinforced and reinforced soil slope model*

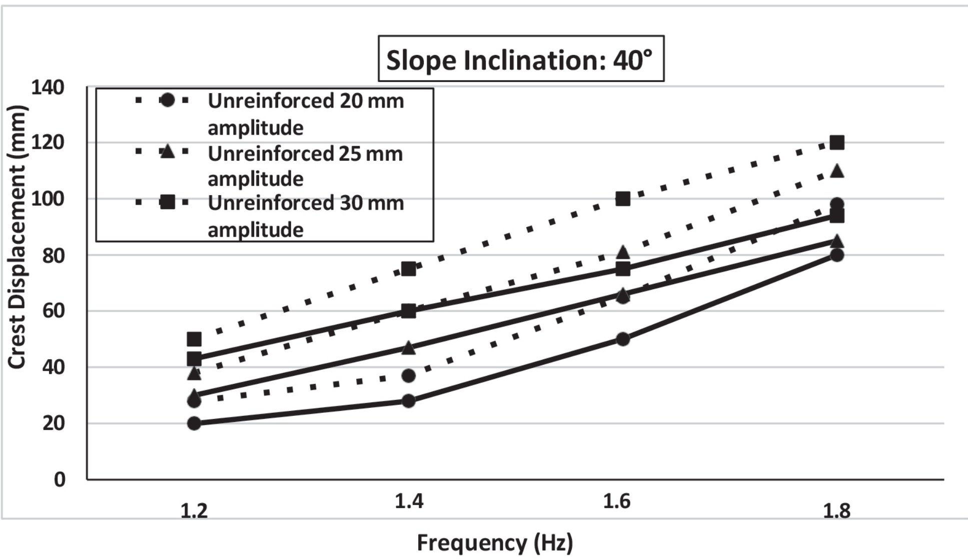



***Figure 8*** *Effect of frequency and amplitude on 40° unreinforced and reinforced soil slope model*

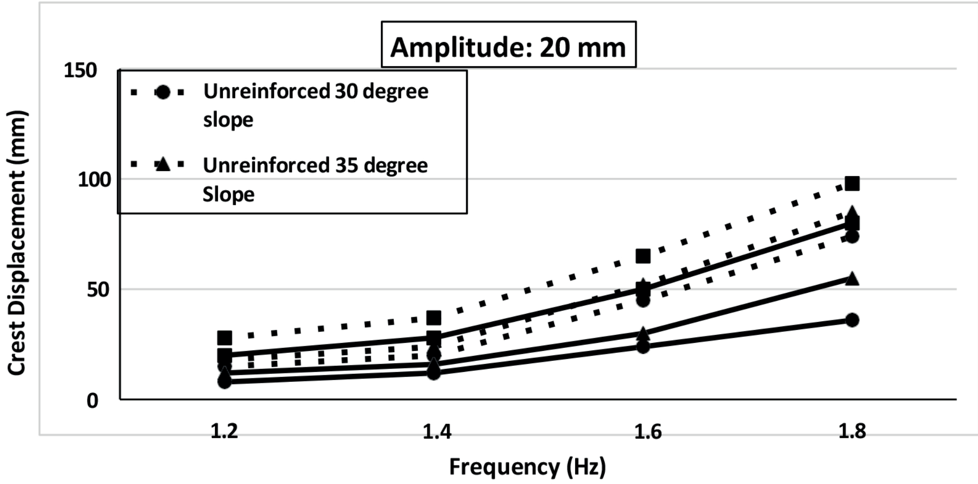



***Figure 9*** *Effect of frequency and slope inclination on 20 mm amplitude on unreinforced and reinforced soil slope model*

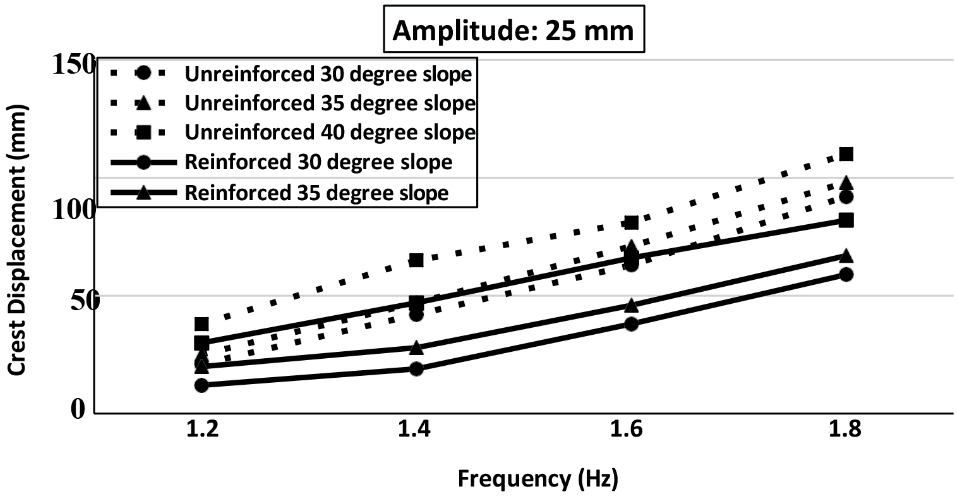



***Figure 10*** *Effect of frequency and slope inclination on 25 mm amplitude on unreinforced and reinforced soil slope model*

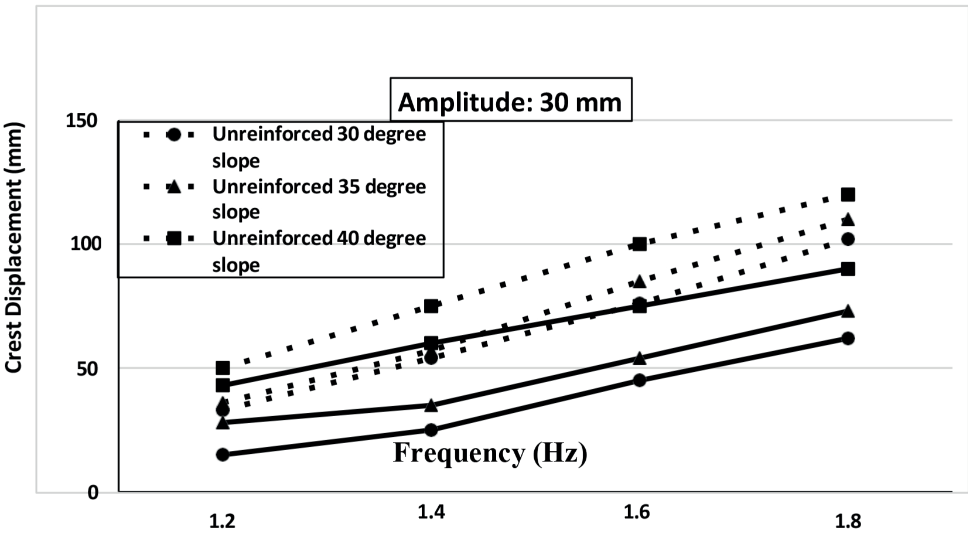



***Figure 11*** *Effect of frequency and slope inclination on 30 mm amplitude on unreinforced and reinforced soil slope model*

at this frequency lead to increased deformation of the soil slope. Similar trends are observed in subsequent trials at frequencies of 1.4, 1.6, and 1.8 Hz. It is found that by providing reinforcement, the crest displacement is decreased for amplitude of 20, 25 and 30 mm for the same frequency.

Figure 8, presents the results of tests conducted on an unreinforced and reinforced soil slope model inclined at 40° under varying frequencies. In the first trial at a frequency of 1.2 Hz, the crest displacement increases from 28 mm to 50 mm as the amplitude rises from 20 to 30 mm. This suggests that the higher amplitudes at this frequency result in increased deformation of the soil slope. A similar trend is observed in subsequent trials at frequencies of 1.4, 1.6, and 1.8 Hz.

Figure 11 provides valuable insights into the dynamic behavior of the unreinforced soil slope at a 40° inclination, highlighting the influence of varying frequencies and amplitudes on the slope's response. This information is essential for understanding the stability of the slope under different loading conditions, aiding in geotechnical engineering assessments and slope stability analyses. Overall, the data underscores the complex dynamic behavior of the reinforced soil slope, offering valuable insights for engineers and researchers engaged in geotechnical assessments and the design of resilient slope structures. Figures 9, to 11 represent the experimental results of the soil slope model for 300 mm height at 30°, 35° and 40° slope inclination with varying amplitude of 20 mm, 25 mm and 30 mm.

From the above Figures 9-11 it is observed that with the increase of slope inclination, the crest displacement increases. By providing reinforcement the crest displacement is decreased by 21 to 47%. When the tests were performed for the frequency 0.2 to 1 Hz there was not much crest displacement observed. At the frequency of 1.8 Hz, a considerable displacement was observed. Hence, the applied frequencies selected were 1.2 Hz to 1.8 Hz. Similarly at amplitudes of 5 to 15 mm a very small displacement was observed. Hence, for significant displacement applied amplitudes were selected as 20 mm, 25 mm and 30 mm.

The results of the research indicate a clear relationship between the displacement and factors such as frequency, amplitude, and slope angle. The significant reduction in crest displacement in reinforced soil slopes compared to unreinforced ones suggests that reinforcement effectively mitigates the destabilizing effects of seismic loading. This can be attributed to the increased shear strength and confinement provided by reinforcement, which enhances the slope's ability to resist deformation under dynamic conditions. The observed 21 to 45% reduction in displacement highlights the critical role of reinforcement in improving the slope stability, particularly in scenarios with high-frequency and high-amplitude seismic events.

The pronounced increase in displacement with steeper slope angles, particularly at 35° and 40°, can be explained by the increased gravitational forces acting on the slope, which exacerbate the tendency for soil to move downslope. As the slope angle increases, the driving forces surpass the resisting forces more easily, leading to greater deformation. The sharp rise in displacement at these steeper angles underscores the importance of considering slope geometry in stability assessments, as well as the need for effective reinforcement strategies to counteract the increased risk of failure in steep slopes under seismic loading.

## 5 Conclusion

In summary, the extensive examination of slope stability analysis, with a specific focus on both reinforced and unreinforced soil slopes, has yielded valuable insights into how the slopes behave under various conditions, such as frequency, amplitude, and slope angle. The findings suggest a noticeable correlation between the displacement and increases in frequency and amplitude, indicating that both reinforced and unreinforced soil slopes experience greater displacement as these factors intensify. A significant discovery from this research is the substantial reduction in crest displacement observed in reinforced soil slopes compared to unreinforced ones. The incorporation of reinforcement led to a remarkable 21 to 45% decrease in crest displacement, underscoring the efficacy of reinforcement techniques in improving slope stability.

Moreover, the research emphasizes the responsiveness of slope displacement to alterations in the angle of the slope. As the incline of the slope rises, there is a corresponding elevation in displacement, illustrating a direct correlation between the steepness of the slope and deformation. Specifically, at more pronounced angles such as 35° and 40°, the displacement demonstrates a significant increase, with respective increments of 9 to 18% and 35 to 65% compared to the 30° slope.

By carefully selecting a scale factor of 1/10 and validating it against theoretical predictions, we ensured the relevance of our findings to the real-world applications. Despite the criticisms that results could be predictable without experiments, our research demonstrates the necessity of empirical validation. By conducting the controlled experiments, this research provides tangible data that substantiates theoretical models and enhances their applicability in practice. This approach not only validates physical modeling methodologies but enriches the scientific understanding as well, by uncovering nuances and complexities that theoretical predictions alone may overlook. Thus, our study contributes robust insights that advance both theoretical frameworks and practical applications in geotechnical engineering, particularly in seismic hazard assessment and mitigation strategies.

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**Conflicts of interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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