Geosfera Indonesia
p-ISSN 2598-9723, e-ISSN 2614-8528
available online at : https://jurnal.unej.ac.id/GEOSI
Vol. 10 No. 2, August 2025, 146-165

https://doi.org/10.19184/geosi.v10i2.53689

Research Article

Experimental Investigation of Wrap-Faced Reinforced Soil Embankments on Soft Clay: A Sustainable Solution for Infrastructure Development in Bangladesh

Shoma Hore[1], Mosharof Al Alim[2] and Ripon Hore[3]*
[1]Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
[2]LGED, Dhaka, Bangladesh
[3] East West University, Bangladesh
* Corresponding author; e-mail: riponhore@gmail.com

ARTICLE INFO
Received :
16 March 2025

Revised :
17 June 2025

Accepted :
4 July 2025

Published :
14 July 2025

ABSTRACT

Wrap-faced reinforced soil retaining walls are a widely accessible solution globally, especially in areas where land use is a concern. The wrap-faced layer requires less space on both sides of the wall, making it a more economical and efficient option, and it is less vulnerable to dynamic loading. Incorporating dynamic loading in the design phase is crucial; however, current embankment projects in Bangladesh do not account for this aspect. Traditionally, sand embankments are constructed atop soft clay layers in road and railway embankment projects in Bangladesh. This research proposes the use of a wrap-faced embankment system on soft clay, piloted based on shake table test results conducted at the Bangladesh University of Engineering and Technology. Various governmental agencies, including the Roads and Highways Department, Local Government Engineering Department, and Bangladesh Railway, are involved in the construction of embankments, which typically require large land areas, especially for embankments with slopes of 1:2 or 1:3. This significant land requirement often becomes a limitation. In contrast, the wrap-faced embankment system offers a viable solution to the land scarcity issue, as it minimizes horizontal space usage and reduces construction costs compared to traditional embankments. This research details the proposed construction process and the modeling of the wrap-faced embankment system, offering insights into its potential for improving embankment design and land utilization in Bangladesh. The research evaluated the dynamic behavior of wrap-faced embankments on soft clay through PLAXIS 3D numerical modeling and shake table experimentation. The results indicated a consistent decrease in displacement with increased surcharge load. This confirms the potential of wrap-faced systems to enhance embankment stability during seismic events in Bangladesh.

Keywords: Shake table; Wrap faced reinforced soil wall; PLAXIS 3D Geotextile and Surcharge load

INTRODUCTION

Embankments are critical structures for the transportation network in Bangladesh, particularly in railway and roadway construction. However, these embankments are often vulnerable to damage due to softening of the soil-foundation under dynamic loading conditions, such as seismic activities or sinusoidal waves, which can lead to significant structural issues. In many cases, the effects of excess p water pressure and soil softening due to seismic excitation are not well understood or adequately incorporated into the design phase. The interaction between dynamic forces and the behavior of clayey soils under such conditions remains a complex challenge, as it is uncertain under which specific shaking conditions damage might be induced and whether the softening of clayey soils should be considered in seismic design [1], [2].

Soft soils from Dhaka, Bangladesh, were used to simulate the soil-foundation system, providing a closer approximation of real-world conditions. The study is driven by the need to address the issues of soil-foundation softening under seismic loading, especially for embankments constructed on soft clay. The primary focus of this experimental investigation is to understand how seismic forces interact with the clayey foundation and the subsequent impact on the structural integrity of the embankments, including the behavior of wrap-faced embankments, which are increasingly being used in Bangladesh for their space-saving benefits and resistance to dynamic loading [1]. Previous studies have highlighted the importance of considering dynamic soil properties in the design of embankments under seismic conditions [2], [3]. The results of this research will provide valuable insights into the dynamic properties of soil, specifically the changes in displacement due to seismic excitation, and contribute to the understanding of the softening effects in clayey soils. These findings will serve as a foundation for future studies and practical applications for improving the stability and performance of wrap-faced embankments in seismic regions. The proposed study also contributes to the growing body of knowledge on the earthquake response of embankments, emphasizing the need to incorporate dynamic soil-structure interaction into the design process for enhanced resilience. This work is expected to inform the development of more accurate and reliable seismic design guidelines for embankments in Bangladesh, with potential implications for other regions with similar geotechnical challenges [4], [5]. This research aims to explore the dynamic behavior of soft clayey soil foundations, particularly their displacement responses under harmonic waves, using shake table tests.

The impact of shake table tests and numerical techniques on the behavior of soil-structure interactions under dynamic loading has been the subject of numerous studies carried out worldwide. The impact of base shake frequency on the dynamic response of both reinforced and unreinforced soil slopes was investigated by Srilatha et al. [6]. In order to assess the soil-cement-bentonite (SCB) slurry wall, which is frequently utilized in geotechnical applications, Xiao et al. [7] investigated the earthquake response of a slurry wall and introduced a mini-scale shake table test. According to Suzuki et al. [8], reinforced soil structures in Japan suffered little damage during recent seismic events. In order to evaluate the seismic behavior of reinforced soil, walls composed of sand, cement-treated clay, and clay, they also performed shake table tests. Krishna & Latha [9] tested model walls in a laminar box using shake tables and concentrated on geotextile-reinforced wrap-faced soil-retaining walls. Their research shed light on how backfill relative density affects reinforced soil wall performance under seismic loads.

Several more investigations have delved deeper into this area, examining the impact of reinforcement and soil characteristics under dynamic circumstances [10]. Celebi et al. [11]; Latha & Manju [12]; Latha & Varman [13] and Krishna & Latha [9] all added to the expanding body of knowledge by investigating the effects of various elements, including reinforcement and backfill density, on the seismic performance of soil-retaining walls. In their study, Kumar & Mishra [14] examined the impact of soil-structure interaction in earthquake-prone multi-story buildings and found that pile foundations produced less lateral displacement than isolated or mat foundations. In a related study, Chen et al. [15] examined how a five-story steel moment-frame building isolated by triple friction pendulum bearings responded to an earthquake. Moreover, studies conducted by Reitherman [16], Hore [17], Sabermahani et al. [18] and Hore [19] demonstrated how pounding between structures under seismic loading causes notable changes in response forces and displacements, which adversely affects the structural performance.

Numerous studies in Bangladesh have used both numerical and experimental modeling to investigate the behavior of wrap-faced embankments on soft clay, such as those conducted by Hore [20]; Chakraborty [21]; Hore et al. [22]. Nonetheless, research on the use of wrap-faced embankments in actual field settings is still lacking. To improve resistance to earthquakes and dynamic wave forces, this study suggests a prototype wrap-faced embankment system for soft Bangladeshi soil. In order to replicate the dynamic behavior of clayey soil in Dhaka, where a sand retaining wall was built on top of the soft clay and subjected to seismic loading, a shake table testing platform was created.

This paper addresses the lack of seismic design methodologies for embankments on soft clay in Bangladesh by proposing wrap-faced reinforced systems as a viable solution for seismic resilience and land optimization. Twelve shake table tests in all were carried out, both numerically and physically, to examine the effects of displacement at various locations under various surcharge pressures and accelerations. The findings advance knowledge of wrap-faced embankments' seismic performance and offer a design layout for embankments in Bangladesh that prioritizes their ability to withstand earthquakes and withstand dynamic loading scenarios. While international research has validated the effectiveness of reinforced soil systems under seismic conditions, especially in South Asia, there is a lack of experimental studies focusing on soft-clay foundations in real-world scenarios. This study aims to bridge the gap by performing both physical and numerical simulations of wrap-faced embankments built on soft clay, utilizing soils and geotechnical profiles representative of Bangladesh. This study utilizes site-specific soils from Bangladesh to advance recent progress in the dynamic testing of geosynthetic-reinforced systems [8], [23], [11] introducing a novel experimental-numerical framework to analyze the seismic responses of wrap-faced embankments situated on soft clay. The combined approach of physical shake table testing and PLAXIS 3D modeling aims to provide advanced insights into displacement behavior under varying surcharge and seismic intensities.

GEOLOGICAL CONDITIONS OF BANGLADESH

Large alluvial deposits and a variety of geological formations, such as the Plio-Pleistocene Barind Clay, Madhupur Clay, and Lamaic Region Clay, are features of Bangladesh, the largest delta in the world. The thickness of the sediment varies, ranging from over 22 kilometers close to Dhaka to roughly 128 meters in the northern areas where granite is extracted. About 250 rivers have shaped the nation, adding to the abundance of sediment deposits. The Bengal Basin, the Chittagong Hill Tracts, and the Stable Platform are the three tectonic zones that make up Bangladesh's geology. Coal in Dinajpur, gas in the south and east, limestone deposits, heavy minerals at Cox's Bazar, and Bijoypur Clay in Netrokona are examples of natural resources. The development of infrastructure is complicated by the soft soil conditions, which call for geotechnical studies. Notably, a pilot project site in Netrokona District is suggested for additional investigation and study, highlighting the region's strategic significance for geological research and mineral extraction that are necessary for sustainable development. The map of soft soil thickness is displayed in Figure 2. The lithological map indicates considerable soft soil thickness in the Netrokona District, highlighting its vulnerability to seismic loading from clayey deposits. The objective of the paper is explicitly influenced by this geotechnical context: to propose a resilient wrap-faced embankment system appropriate for soft clay conditions. Understanding the subsurface lithology facilitates the optimization of reinforcement design and surcharge load distribution, thereby enhancing seismic performance and extending embankment longevity.

METHODS

The computer-controlled system used in this study to simulate horizontal shaking actions related to dynamic loading is called a shake table facility. The testing platform is square in shape, measuring 2.5 x 2.5 m^2, and is made of steel plates for structural stability. With a payload capacity of about 1100 kg, the platform can be used for a variety of tests with different kinds of soil and materials. With an acceleration range of 0.05g to 2g, the shake table can simulate different earthquake intensities. The system's frequency range is 0.05 Hz to 50 Hz, and its maximum amplitude is ±200 mm. This allows it to simulate both low- and high-frequency seismic events. Furthermore, the shake table's maximum velocity is 0.3 m/s, which is necessary to replicate authentic shaking effects throughout the tests.

Figure 3 illustrates the shake table test machine, which is an essential tool for researching how soil and structures behave dynamically during seismic activity. A laminar box, shown in Figure 4, is set up on the shake table to carry out the experiments. In order to accurately capture and analyze the lateral displacements and vertical stresses caused by the movement of the shake table, this laminar box is used as the testing environment for simulating soil-foundation interactions. In a controlled setting, the laminar box makes it possible to test how various soil and structural systems—like wrap-faced embankments—behave under dynamic loading scenarios that mimic actual seismic occurrences.

To reduce boundary effects during the tests, a laminar box was built as part of the shake table apparatus. During dynamic loading, the soil can move naturally because the laminar box neither prevents nor encourages soil displacement. Each of the 24 hollow aluminum layers that make up the laminar shear box is intended to permit unrestricted soil movement within the testing area. Bangladesh University of Engineering and Technology (BUET) developed these frames, guaranteeing their functionality and longevity. In order to accommodate the test specimen and guarantee consistent behavior under seismic forces, each layer in the laminar box has internal dimensions of 915 mm × 1220 mm × 1220 mm. Figure 1 illustrates the overall workflow followed in this study, from sample preparation to validation of numerical results, ensuring an integrated assessment of wrap-faced embankment behavior under seismic loading.

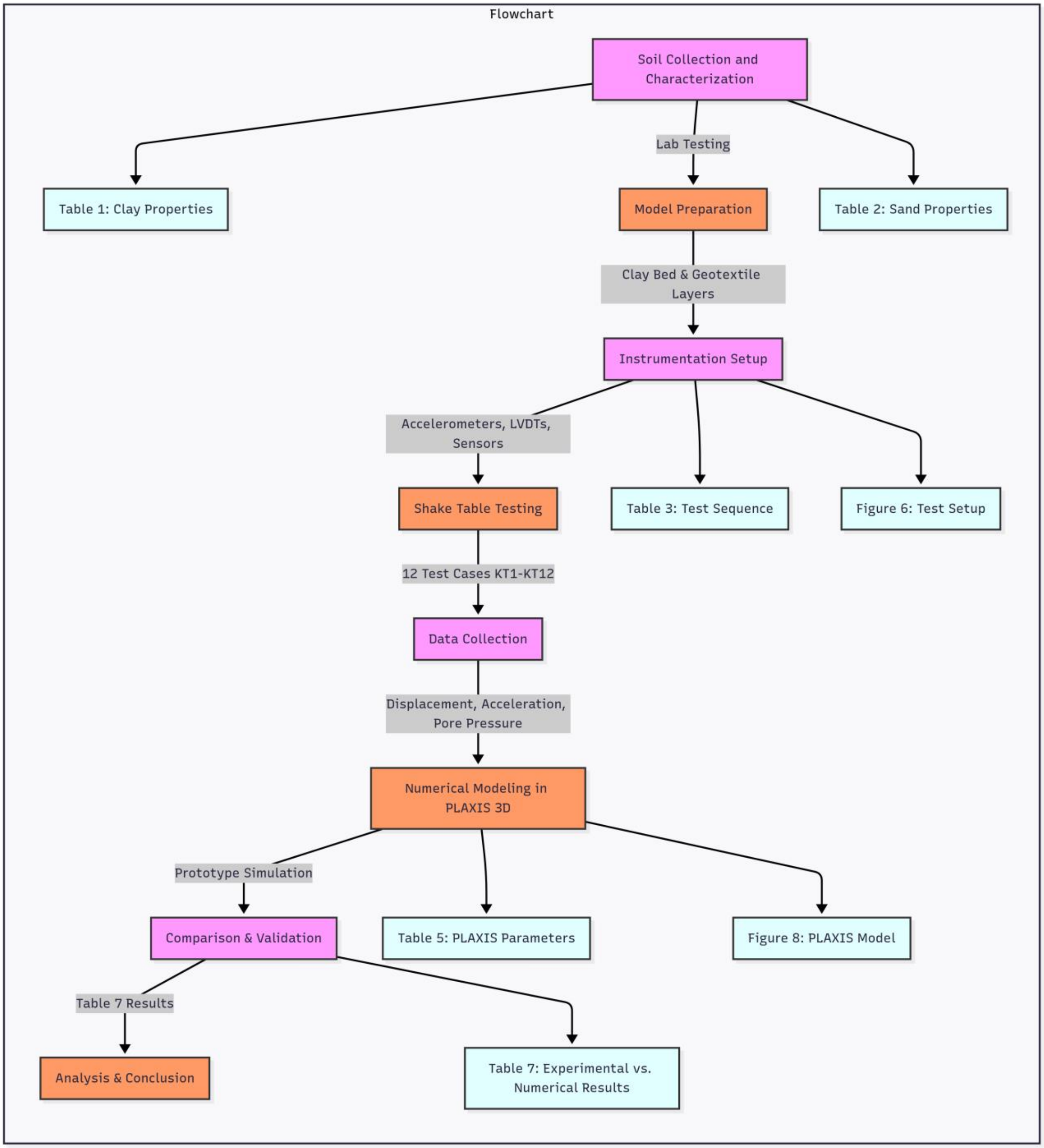

Figure 1. Flowchart showing Research Framework for Evaluating Wrap-Faced Embankments on Soft Clay.

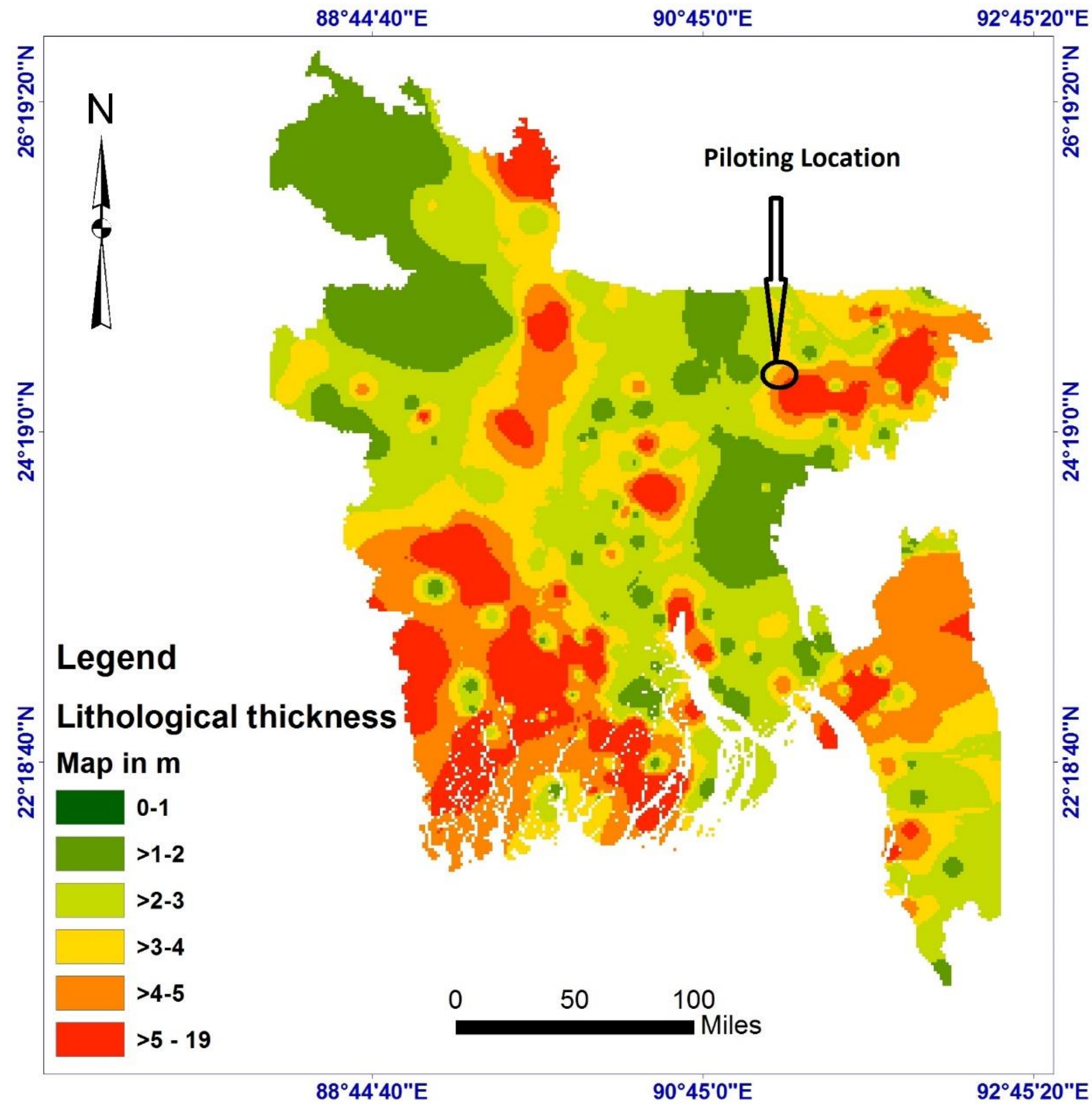

Figure 2. Study area with location of weather stations

Figure 3. Shake table test apparatus

Figure 4. Laminar box mounted on shake table

Sand that was readily available locally was used as the backfill material. The sand is categorized as poorly graded sand (SP) by the Unified Soil Classification System (USCS). The sand has a relative density of 64% and a maximum dry density of 18 kN/m³ and a minimum dry density of 16 kN/m³. The availability of this sand and its ability to replicate the typical soil conditions in the study area led to its selection. The experiments also used soft clay soil from Dhaka, Bangladesh, in addition to the sand. It was discovered that the clay had a water content of 23% and a liquid limit of 40%. A soil sample with a water content of 14% was obtained by adjusting the water content to 50% of the liquid limit (1.25 times the liquid limit) in order to prepare it for testing. The clay's unconfined compressive strength (qu) was measured at 28 kPa following loading. The three-meter-thick clay layer used in the tests was typical of the conditions present in the study area.

The process of preparing a reconstituted soil sample is depicted in Figure 5, and Figure 6 shows the test setup schematic diagram. In Figure 7, the wrap-faced embankment model intended for testing is shown. The specific characteristics of the clayey and sandy soils used in the study are shown in Tables 1 and 2, which offer more information about the material's properties and how they relate to the testing environment.

Table 1. Property of clayey soil [1], [22], [23]

Soil type	**γ^*_{unsat} (kN/m^3)**	**γ_{sat} (kN/m^3)**	**C (kPa)**	**ø (°)**	**Specific gravity (G_s)**	**LL**	**PL**	**Coefficient of Permeability (ms^{-1})**	**Porosity**
Clayey	16	18	28	1	2.61	36%	14%	3×10^{-7}	0.65

Table 2. Property of sandy soil [1], [22], [23]

Soil type	**γ^*_{unsat} (kN/m^3)**	**γ_{sat} (kN/m^3)**	**e_{max}**	**e_{min}**	**C_u**	**C_c**	**C (kPa)**	**ø (°)**	**Specific gravity (G_s)**
Sandy	16.6	20	0.87	0.56	2.14	0.64	0	31	2.63

Figure 5. Preparation of clayey layer under embankment

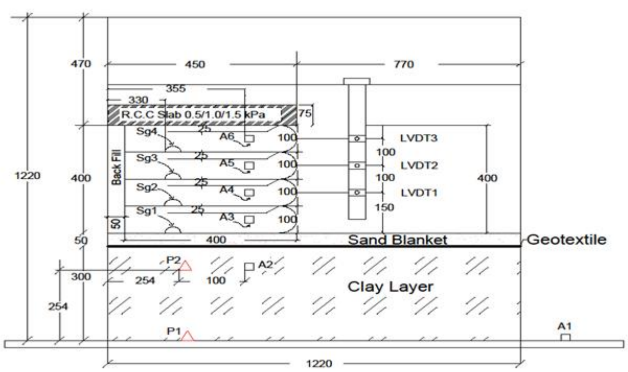

Figure 6. Schematic diagram of typical test

Figure 7. Wrap faced embankment

The shake table tests were conducted in a laminar box that measures 1220 mm in depth and 915 mm by 1220 mm in plan area. In order to help guarantee the stability of the embankment structure during the seismic simulations, the model was built in lifts of equal height, each of which was reinforced by a layer of woven geotextile. As seen in Figure 5, two pore water sensors (P1 and P2) were positioned at key points throughout the model to track the pore water pressure throughout the tests. These sensors were essential for recording how dynamic loading affected the water content of the soil. The model was positioned with six acceleration sensors (A1, A2, A3, A4, A5, and A6) in addition to the pore water sensors. The acceleration that the soil experienced during the shaking events was measured by placing sensors A1 and A2 inside the clay soil layers. Analyzing the dynamic behavior of the embankment under various loading scenarios required the use of these acceleration readings.

The displacement of the structure under seismic loading was measured by placing three displacement sensors (LVDT1, LVDT2, and LVDT3) at strategic locations along the embankment. These sensors provided real-time data on the movement of the embankment and helped in assessing the structural response, including any potential deformation caused by dynamic forces. The test sequence and experimental setup are summarized in Table 3, providing a detailed overview of the testing process, sensor placement, and the stages of data collection. This setup was designed to capture comprehensive data on the embankment's behavior during shake table tests, allowing for a thorough analysis of the structural performance under earthquake-like conditions.

Table 3: Test Sequence [9], [26]

Test Name	Surcharge Load*, kPa	Base Acceleration, g	Frequency, Hz	Relative Density, %
KT1	0.5	0.05	1	64
KT2	1.00	0.05	1	64
KT3	1.50	0.05	1	64
KT4	0.5	0.1	1	64
KT5	1.00	0.1	1	64
KT6	1.50	0.1	1	64
KT7	0.5	0.15	1	64
KT8	1.00	0.15	1	64
KT9	1.50	0.15	1	64
KT10	0.5	0.2	1	64
KT11	1.00	0.2	1	64
KT12	1.50	0.2	1	64

*A Scale factor of 10 was used for Phototype

Reinforcement and Surcharge Load

In this study, non-woven polypropylene multifilament geotextile (DF50) was used to reinforce sand. Table 4 provides a summary of the geotextile properties. A universal tensile testing machine was used to ascertain the geotextile's tensile characteristics. In both the X and Y directions, the average initial modulus (Ei) and secant modulus (Es) were found to be: Ei = 23 kN/m and Es = 181 kN/m for the X direction, and Ei = 28 kN/m and Es = 173 kN/m for the Y direction. These values are crucial for the design of the embankment reinforcement because they show the stiffness and deformation behavior of the geotextile under tensile stress.

Three different levels of surcharge loads—0.5 kPa, 1.0 kPa, and 1.5 kPa—were applied in this study to simulate the effect of different loading conditions on the embankment. The surcharge loads were applied using concrete slabs, with weights corresponding to each load level: 43 kg for the 0.5 kPa surcharge, 28.5 kg for the 1.0 kPa surcharge, and 14 kg for the 1.5 kPa surcharge. These surcharge loads were critical for evaluating the embankment's response to applied pressure and simulating real-world loading conditions, such as the weight of vehicles or other loads on top of the embankment structure.

The combination of reinforced sand using geotextile and the application of surcharge loads provided valuable insights into the behavior of the embankment under dynamic loading conditions, specifically under the influence of seismic forces. The experimental setup and testing methodology were designed to mimic real-life conditions, ensuring that the results accurately reflect the performance of the embankment in the field. The reinforcement strategy using geotextile and load simulations is consistent with methods described by Krishna & Latha [9], and Chakraborty et al. [21].

Table 4: Geotextile specification.

No.	Details	DF 50
1.	Reinforcement type	mechanically bonded needle punched
2.	Yarn material (staple Fibre)	Polypropylene
3.	Mass/unit area (gsm)	322
4.	Aperture Size , O_{95} (µm)	130
5.	Thickness (mm)	2.54
6.	Ultimate Tensile Strength (KN/m)	15.5

Instrumentation

Six accelerometers in all were positioned carefully throughout the experimental setup to measure the accelerations of the sand wall, clayey soil, and shaking table. During the shake table tests, these accelerometers gave vital information about the system's dynamic response. Additionally, the sand wall's horizontal displacements were tracked using eight Linear Variable Displacement Transformers (LVDTs): LVDT1, LVDT2, and LVDT3. The degree of movement and deformation of the embankment under seismic loading was evaluated with the aid of these displacement sensors. Two pore water pressure sensors (P1 and P2) were positioned at strategic points in the model to track variations in the pore water pressure within the soil. Important information about the soil's response to dynamic loading was obtained from these sensors, especially regarding the impact of seismic forces on pore water pressure and the possibility of liquefaction or other changes in soil behavior during shaking.

Furthermore, the strain experienced by various model components was measured using four strain gauges (Sg1, Sg2, Sg3, and Sg4). By providing information on the internal forces in the soil and reinforced structure, these strain gauges aided in the assessment of the embankment's structural soundness under dynamic loading circumstances. To guarantee accuracy and reliability in data collection, every sensor was meticulously positioned at predetermined points throughout the physical model's layer-by-layer construction. The arrangement and positioning of the instruments are detailed in Figure 3, ensuring that the measurements captured the dynamic behavior of the system throughout the tests. In total, fifteen data channels were employed to monitor the various parameters, allowing for comprehensive analysis and interpretation of the embankment's response to seismic activity. Instrumentation layout and sensor calibration follow protocols described in Suzuki et al. [8].

Development of 3D Numerical Model

A 4-meter wrap-faced embankment was modeled numerically for this study using PLAXIS 3D software, which employs quadratic tetrahedral 10-node elements for analysis. Because it enables the creation of complex finite element models through straightforward graphical input procedures, this software is especially well-suited for geotechnical and structural analyses, allowing for accurate and efficient simulations. Furthermore, the enhanced output facilities of PLAXIS provide a comprehensive presentation of the results, facilitating detailed interpretation of the model's behavior under dynamic loading conditions. The study used a reduced 1/10 scaled model for the shake table experiment, as depicted in Figure 3. The water table was set at the 0.00 level, and three types of surcharge loads — 5 kPa, 10 kPa, and 15 kPa — were considered to model the traffic load applied to the embankment. The geotextile reinforcement in the numerical model had a tensile strength of 2500 kN/m. To model the soil behavior, both the fill and the entire soil material were represented using the Mohr-Coulomb failure criterion, which is commonly used for soils in geotechnical modeling.

Table 5 summarizes the soil properties utilized in the PLAXIS modeling, which include parameters such as cohesion, friction angle, and density, critical for simulating the embankment's response under seismic loading. Numerical modeling using PLAXIS 3D has been an essential component of this study, allowing the simulation of various surcharge loads and dynamic forces to predict the behavior of the wrap-faced embankment under earthquake-like conditions. It is important to note that while low-stress 1-g shake table tests are effective in simulating seismic conditions, they may not fully replicate the behavior of the full-scale prototype embankment. As noted by Latha & Manju [12], scaled models typically provide valuable insights but have limitations in accurately predicting the behavior of the full-scale embankment, especially in terms of stress distribution and large-scale deformation. Despite these limitations, the numerical modeling provides a significant contribution to understanding the performance of the wrap-faced embankment under dynamic conditions.

Table 6 shows the prototype to model scale, which is N = 10, taking into account limitations resulting from the size of the model container and the shaking table's capacity. The scaling factors for this study were taken into consideration as an exponent of confining pressure (α) = 0.5 for sand [13]. Figure 8 displays the modelling of the wrap-faced embankment created by PLAXIS 3D. Figure 10 illustrates the PLAXIS 3D numerical model of the wrap-faced embankment, highlighting the geometry, mesh refinement, and boundary conditions employed to replicate realistic field behavior. The figure illustrates the embankment structure built on soft clay, with accurately defined reinforcement layers and surcharge loads applied to the upper surface. The mesh density is greater near the reinforcement layers and foundation interface to enhance precision in stress-strain prediction. This configuration facilitated the capture of the deformation pattern observed in the experimental tests, thereby corroborating the consistency of the numerical and physical modeling.

Table 5: Soil parameters used in the PLAXIS 3D modelling.

Material	**γ_{sat} kN/m^3**	**Soft soil Model**	**Hardening soil model**	**C (kN/m^2)**	**Φ (°)**
Sand	20		Reference stiffness modulus, Stiffness, $E_{50}^{ref}=8.70\times10^5$kN/m^2	0	31
Clay	18	Modified stiffness index, λ=0.05 Modified swelling index, K=0.01		28	1

Table 6: Scale factors of selected engineering variables.

Description	**Parameter**	**Scale factor**	**Scale factor M/P**	**Scale factor P/M**
Acceleration	A	1	1	1
Length	L	1/N	0.10	10
Stress	Σ	1/N	0.10	10
Strain	G	$1/N^{1-\alpha}$	0.32	3.125
Displacement	D	$1/N^{2-\alpha}$	0.031	32.25
Frequency	F	$N^{1-\alpha/2}$	5.62	0.18
Force	F	$1/N^3$	0.001	1000
Time	T	$1/N^{1-\alpha/2}$	0.178	5.62

*P-Prototype; M-Model

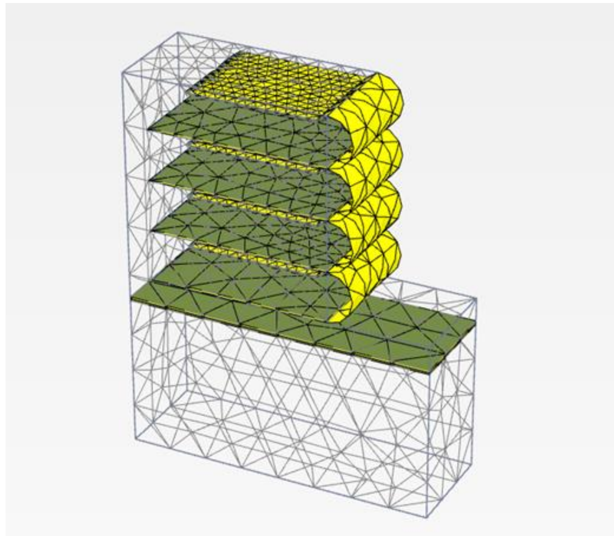

Figure 8. Wrap faced modelling by PLAXIS 3D

Analysis

The wrap-faced embankment was numerically modelled and analyzed using the PLAXIS 3D program. The Mohr-Coulomb model was first used in this study as a straightforward method to model the embankment's behavior. In the analyses, the embankment was modelled under drained conditions, while the clay foundation was modelled under undrained conditions. Two types of soils were used in the study: soft clayey soil and sandy soil. The soft clayey soil layer was modelled using the reconstituted clay model, while the sand wall was modelled using the Hardening Soil model to better capture the behavior of the sand material under loading. Figure 9 illustrates the wrap-faced embankment modelling process, showing the different phases of the analysis conducted using PLAXIS 3D.

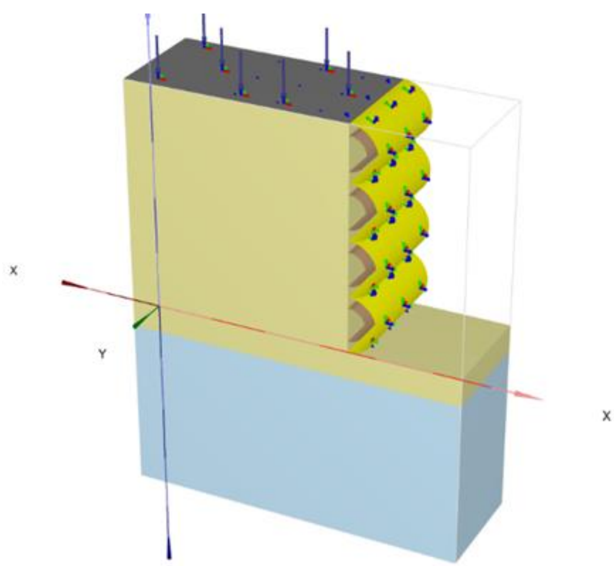

Figure 9. Wrap faced embankment modelling (PLAXIS 3D)

RESULTS

Shake table tests were used in this study to test twelve test patterns, and PLAXIS 3D software (Finite Element Method) was used for numerical analysis and validation. At a constant frequency of 1 Hz, three distinct surcharge loads—0.5 kPa, 1 kPa, and 1.5 kPa—were applied. The experiments were conducted using the four acceleration levels (0.05g, 0.1g, 0.15g, and 0.2g). The different model tests with various parameters are compiled in Table 2. The entire wall height (H) of the embankment wall was 400 mm, and it was built on soft clay with an unconfined compressive strength of 20 kPa. Twenty sinusoidal motion shaking cycles were applied to the wall. For every shaking table test, a new model wall with a relative density of 64% had to be built. Exams KT1, KT2, and KT3 (Acceleration of 0.05g) Figures 10 through 13 show how the model wall's face displacement behaves under various surcharge pressures. As the surcharge pressure increased in the case of 0.05g acceleration, the displacement decreased. The experimental and numerical maximum deformations at 0.5 kPa surcharge pressure were 11.80 mm ($\delta h/H$ = 3.0%) and 12.8 mm ($\delta h/H$ = 3.2%), respectively. The experimental maximum deformation was 11.76 mm ($\delta h/H$ = 2.94%) and the numerical maximum deformation was 12.3 mm ($\delta h/H$ = 3.1%) for a surcharge pressure of 1.5 kPa. The displacements decreased as the surcharge pressure increased at all elevations. The findings of this study were in line with those of and.

Table 7 displays the outcomes of the displacement profiles. In both the experimental and numerical analyses, the topmost layer of the embankment wall showed the greatest deformations. With errors ranging from 3.32% to 3.59%, the top layer had the largest error. For tests KT1, KT2, and KT3, the discrepancy between the experimental and numerical results was comparatively small. Tests KT4, KT5, and KT6 (0.1g Acceleration) In tests KT4, KT5, and KT6, a similar pattern was observed, where displacement decreased with increasing surcharge pressure. For 0.5 kPa surcharge pressure, the maximum deformation was 13.56 mm ($\delta h/H$ = 3.39%) experimentally, and 14.20 mm ($\delta h/H$ = 3.56%) numerically. For 1.5 kPa surcharge pressure, the maximum deformation decreased to 13.12 mm ($\delta h/H$ = 3.28%) experimentally, and 13.72 mm ($\delta h/H$ = 3.48%) numerically. The displacement profiles for these tests also indicated that numerical results were slightly higher than experimental results, with differences ranging from 3.14% to 4.28% (see Table 7).

Tests KT7, KT8, and KT9 (0.15g Acceleration) The highest deformation in tests KT7, KT8, and KT9 was 14.92 mm ($\delta h/H$ = 3.73%) at a surcharge pressure of 0.5 kPa, and it dropped to 14.16 mm ($\delta h/H$ = 3.54%) at a surcharge pressure of 1.5 kPa. The numerical displacement results from PLAXIS 3D were 1.8% higher than the experimental results. The numerical displacement profiles for tests KT7, KT8, and KT9 showed similar trends to the experimental results but with slightly higher values, as shown in Figure 11. Tests KT10, KT11, and KT12 (0.2g Acceleration) For tests KT10, KT11, and KT12, the maximum displacement decreased from 15.8 mm ($\delta h/H$ = 3.95%) at 0.5 kPa surcharge pressure to 15.2 mm ($\delta h/H$ = 3.8%) at 1.5 kPa surcharge pressure. The corresponding numerical displacement decreased from 16.4 mm ($\delta h/H$ = 4.1%) to 15.6 mm ($\delta h/H$ = 3.9%). The results showed that experimental displacements were smaller than numerical results, with a difference of 3.81%, 3.35%, and 3.13% for tests KT10, KT11, and KT12, respectively (see Table 7).

The overall findings suggest that the deformation of the model wall had an inverse relationship to the surcharge pressure at all elevations. This pattern was especially pronounced in the top layer of the embankment wall. In numerical analysis, the displacements in the upper layer were slightly higher than those observed experimentally. The minor differences observed between the experimental and numerical results were attributed to the hardware and software configuration. The average differences in results between experimental and numerical studies for the bottom, mid, and upper layers of the embankment wall were found to be quite small, ranging from 1.69% to 4.75%. These differences were generally within an acceptable margin of error. Figure 14 shows the deformation of the entire model using PLAXIS 3D, providing a detailed visualization of the embankment's response to the applied loads and accelerations. The results from the shake table experiments and numerical simulations offer valuable insights into the behavior of wrap-faced embankments under seismic conditions, particularly in relation to surcharge pressure and acceleration levels.

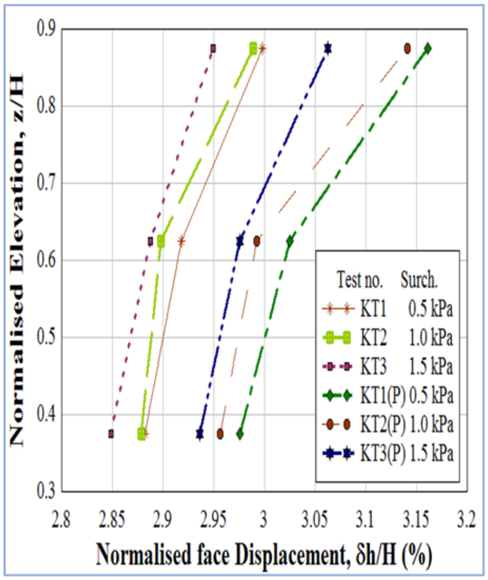

Figure 10. Effect of Surcharge on displacement profile (0.05 g).

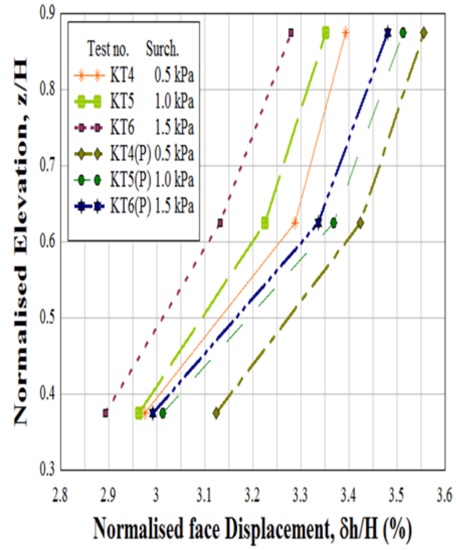

Figure 11. Effect of Surcharge on displacement profile (0.1 g).

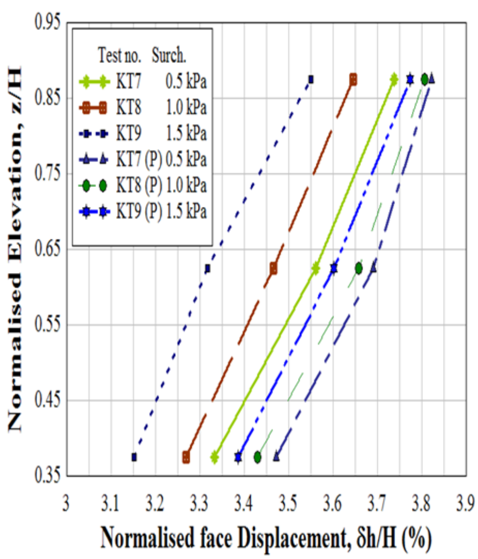

Figure 12. Effect of Surcharge on displacement profile (0.15 g).

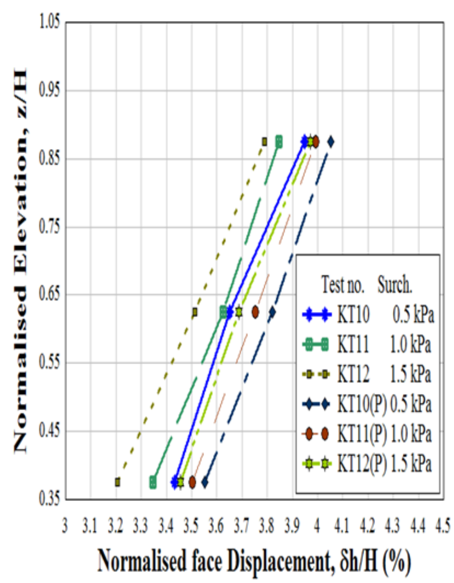

Figure 13. Effect of Surcharge on displacement profile (0.2 g)

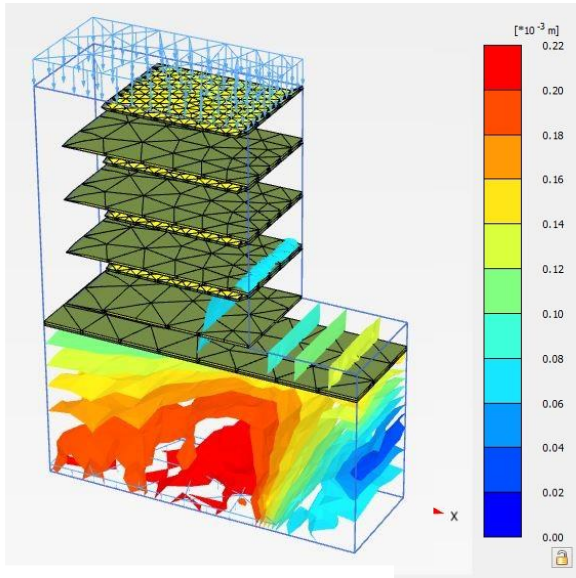

Figure 14. Deformation of embankment at PLAXIS.

Table 7: The experimental and numerical test results

Test Name	Layers of Sand Wall	Experimental Displacement (mm)	Numerical Displacement (mm)	Error with respect to Experimental result (%)	Average Error (%)
KT1	2nd layer (2nd Bottom)	11.39	11.75	3.16	3.34
	3rd layer (Mid)	11.55	11.90	3.03	
	4th Layer (Top)	11.80	12.25	3.81	
KT2	2nd layer (2nd Bottom)	11.57	11.97	3.46	3.59
	3rd layer (Mid)	12.53	12.97	3.50	
	4th Layer (Top)	13.12	13.62	3.81	
KT3	2nd layer (2nd Bottom)	12.61	12.98	2.94	3.32
	3rd layer (Mid)	13.27	13.65	2.87	
	4th Layer (Top)	14.20	14.79	4.15	
KT4	2nd layer (2nd Bottom)	12.83	13.32	3.82	4.28
	3rd layer (Mid)	14.05	14.65	4.27	
	4th Layer (Top)	15.16	15.88	4.75	
KT5	2nd layer (2nd Bottom)	11.51	11.83	2.78	3.14
	3rd layer (Mid)	11.59	11.97	3.28	
	4th Layer (Top)	11.96	12.36	3.35	
KT6	2nd layer (2nd Bottom)	11.85	12.05	1.69	3.45
	3rd layer (Mid)	12.90	13.47	4.42	
	4th Layer (Top)	13.40	13.97	4.25	

Test Name	Layers of Sand Wall	Experimental Displacement (mm)	Numerical Displacement (mm)	Error with respect to Experimental result (%)	Average Error (%)
KT7	2nd layer (2nd Bottom)	13.08	13.42	2.60	3.22
	3rd layer (Mid)	13.86	14.23	2.67	
	4th Layer (Top)	14.58	15.22	4.39	
KT8	2nd layer (2nd Bottom)	13.38	14.01	4.71	4
	3rd layer (Mid)	14.50	15.01	3.52	
	4th Layer (Top)	15.38	15.96	3.77	
KT9	2nd layer (2nd Bottom)	11.53	11.90	3.21	3.55
	3rd layer (Mid)	11.67	12.10	3.68	
	4th Layer (Top)	11.99	12.44	3.75	
KT10	2nd layer (2nd Bottom)	11.90	12.29	3.27	3.81
	3rd layer (Mid)	13.15	13.69	4.11	
	4th Layer (Top)	13.57	14.12	4.05	
KT11	2nd layer (2nd Bottom)	13.33	13.89	4.20	3.35
	3rd layer (Mid)	14.25	14.76	3.58	
	4th Layer (Top)	14.95	15.29	2.27	
KT12	2nd layer (2nd Bottom)	13.73	14.21	3.50	3.13
	3rd layer (Mid)	14.61	15.08	3.21	
	4th Layer (Top)	15.79	16.21	2.66	

Table 7 presents a comparison of experimental and numerical displacements for all test configurations (KT1–KT12) across various sand wall layers. The upper layer exhibits the greatest deformation under dynamic loading, consistent with the amplification of seismic effects towards the surface. The discrepancy between experimental and numerical values remains within 2–5%, indicating robust model validation. As illustrated in Figures 9–12, displacement diminishes under increased surcharge loads, thereby validating the effects of reinforcement and confinement. The consistent trends enhance confidence in utilizing PLAXIS 3D as a reliable simulation tool for predicting embankment behavior under seismic loading.

DISCUSSION

This study was conducted to evaluate the seismic performance of wrap-faced reinforced soil embankments constructed over soft clay foundations—an embankment type not traditionally used in Bangladesh despite its global applicability. Through integrated shake table testing and numerical simulation using PLAXIS 3D, the research explored the displacement, acceleration amplification, pore water pressure, and strain behavior under varying seismic intensities and surcharge loads. The primary result—an inverse correlation between horizontal deformation and surcharge pressure—directly supports the study's objective of assessing seismic stability enhancement through structural confinement. Scientifically, this trend is attributed to the increased overburden pressure from the surcharge, which improves the lateral confinement of the reinforced sand layers, thereby enhancing stiffness and reducing seismic-induced deformation. These results are consistent across both physical and numerical models.

Elevational displacement profiles reveal greater deformation in the upper sections of the embankment, which aligns with dynamic soil behavior theory. Surface layers, being less confined and experiencing higher shear strains, typically undergo more movement during seismic events. This observation highlights the practical need for optimized vertical distribution of reinforcement, with potentially denser reinforcement in upper strata to mitigate surface deformations during earthquakes. The agreement between experimental shake table data and numerical PLAXIS 3D results—with deviations generally within 5%—validates the accuracy of the simulation methodology and confirms the reliability of PLAXIS 3D for modeling wrap-faced systems under seismic loading. Any minor discrepancies may be due to factors such as boundary friction in the physical model, equipment sensitivity, or simplifications in boundary conditions within the numerical model.

Comparison with earlier studies further reinforces the credibility of the current findings. The displacement trends and acceleration amplification observed are consistent with those reported by Krishna & Latha [23], who investigated seismic response of reinforced soil walls using both physical approaches. Their work also emphasized higher deformation at the upper elevations and the role of surcharge in influencing seismic performance. Furthermore, while Chakraborty et al. [21] presented a physical model of reinforced walls, they did not integrate numerical validation, making the dual approach in this study a methodological advancement. Additionally, Sabermahani et al. [18] focused on the impact of harmonic sinusoidal loading rather than real earthquake records, limiting its applicability to field conditions. In contrast, the present study utilized the Kobe earthquake record (1995 Hanshin event), providing more realistic seismic input consistent with natural ground motions expected in tectonically active regions.

This investigation is particularly significant for Bangladesh, where soft clay foundations are prevalent and current embankment designs often lack seismic considerations. The results confirm that wrap-faced systems, due to their compact geometry and confinement effect, offer a promising solution for constructing earthquake-resilient embankments with minimal land requirements. This is especially important for agencies such as the Roads and Highways Department and the Bangladesh Railway, which often face land scarcity issues for infrastructure development. In conclusion, the study presents scientifically validated evidence that wrap-faced reinforced embankments can significantly enhance seismic stability when constructed on soft clay. The findings support the potential integration of this system into national design guidelines. However, further field-scale investigations are recommended to capture long-term behavior, cyclic degradation, and environmental variability under operational loading conditions.

Proposed Wrap Faced Embankment

Bangladesh is indeed an earthquake-prone region, with a history of severe seismic events such as the Great Indian Earthquake of 1897 (magnitude 8.7) and the Bengal Earthquake of 1885 (magnitude 7.0). These earthquakes not only caused extensive damage to building infrastructures but also significantly affected road embankments, highlighting the vulnerability of such structures in the region. The invention of the wrap-faced embankment offers a promising solution to enhance the resilience of road embankments against seismic forces. This innovative design provides greater resistance to severe earthquakes, making it a valuable addition to earthquake-resistant infrastructure in Bangladesh. In addition to earthquake resistance, the wrap-faced embankment can also reduce the land acquisition costs for the government, which is a significant challenge in Bangladesh due to the high demand for land and the associated costs. By using this technology, a large amount of agricultural land can be preserved, leading to increased agricultural productivity. Furthermore, Bangladesh is increasingly vulnerable to the impacts of climate change, particularly the rising water levels of rivers during the rainy season. This phenomenon poses significant challenges for riverbank protection and flood control. The wrap-faced embankment, which introduces vertical reinforcement, provides a novel approach to mitigating wave action and protecting riverbanks against erosion. This method, being used for the first time in Bangladesh, offers hope for enhancing the durability and stability of embankments in the face of climate-related challenges.

Figure 15, showing the proposed layout of the wrap-faced embankment on soft soil in Bangladesh, likely illustrates how this design can be implemented in local conditions to strengthen infrastructure and protect vital land and resources. This approach offers a multifaceted solution to both earthquake resistance and climate adaptation, which could have far-reaching benefits for the country's infrastructure and agricultural sectors.

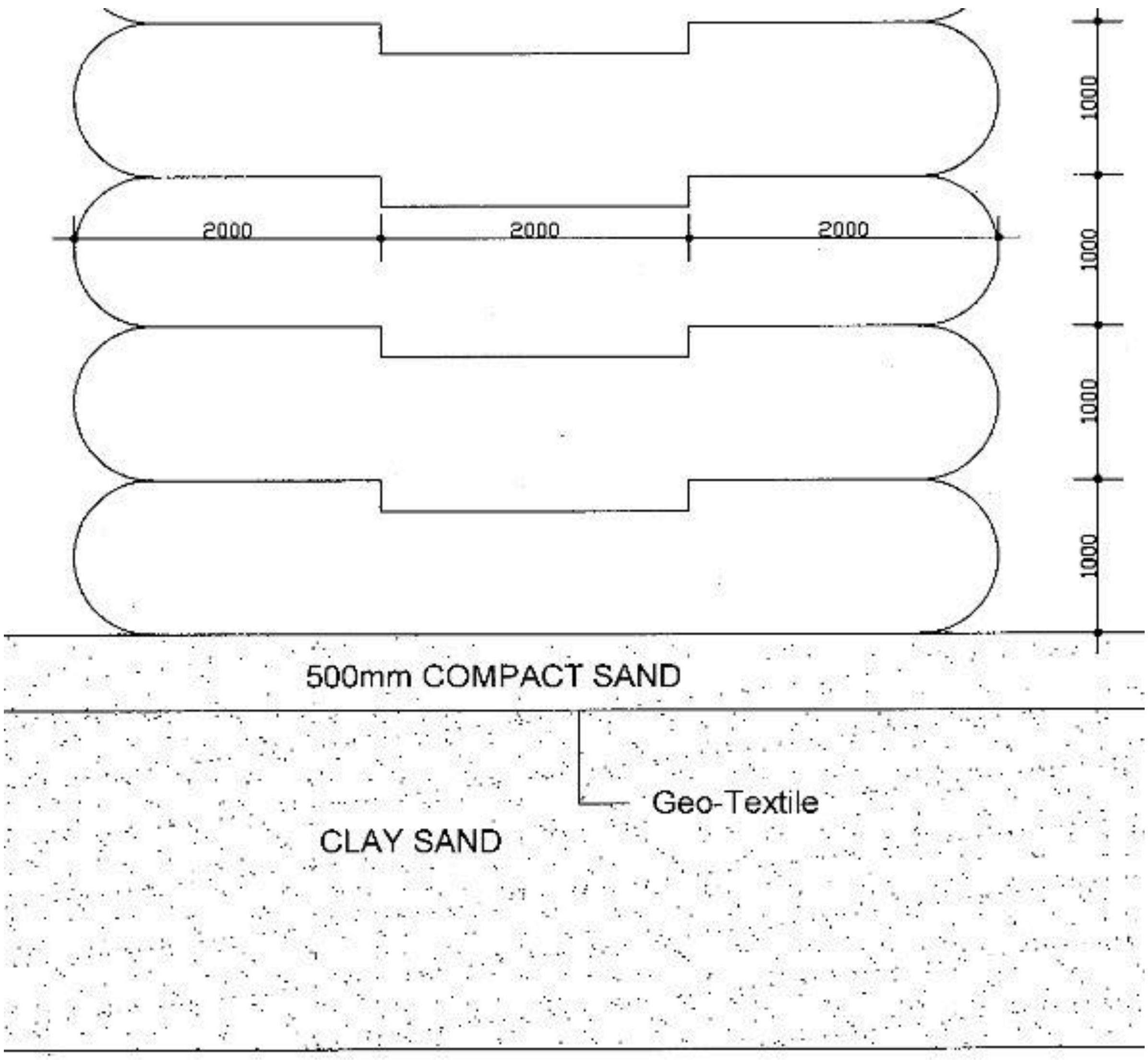

Figure 15. Proposed layout of Wrap Face Embankment

CONCLUSION

For Bangladesh, the shake table test on the wrap-faced embankment over a clay soil foundation is a novel investigation. For the nation's infrastructure to function seismically, embankments on soft clay soils are essential. The results of this study present chances to modernize and improve seismic design guidelines for embankments in these kinds of locations. The test results showed that face deformations increased in tandem with the embankment's elevation. Furthermore, an increase in surcharge pressure resulted in a decrease in displacement at all elevations, confirming the impact of surcharge load on embankment stability. The PLAXIS 3D analysis results corroborated these conclusions as well. Generally speaking, the differences between the experimental results from the shake table tests and the numerical results from the PLAXIS 3D analysis were less than 5%. The insights gained from this research are valuable for understanding the relative performance of wrap-faced embankments, and they provide critical guidance for the design process of such embankments in earthquake-prone regions. This study contributes to the development of more resilient and cost-effective embankment designs, especially in soft soil conditions like those found in Bangladesh.

DECLARATIONS

Conflict of Interest

We declare no conflict of interest, financial, or otherwise.

Ethical Approval

On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent

On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

REFERENCES

[1] R. Hore, S. Chakraborty, K. Kamrul, A. M. Shuvon, and M. A. Ansary, "Earthquake response of wrap faced embankment on soft clay soil in Bangladesh," *Earthquake Engineering and Engineering Vibration*, vol. 22, no. 3, 2023, doi: 10.1007/s11803-023-2194-8.

[2] R. Hore and S. Hore, "Analysis of Dynamic Soil Properties by a Systematic Approach," in *Lecture Notes in Civil Engineering*, Springer Science and Business Media Deutschland GmbH, 2024, pp. 613–618. doi: 10.1007/978-981-97-4355-1_59.

[3] A. Khair, R. Hore, and M. A. Ansary, "Investigation of Site Amplification for the Sedimentary Deposits of DMDP Area in Bangladesh," *Indian Geotech J*, Apr. 2024, doi: https://doi.org/10.1007/s40098-024-00931-8.

[4] Md. M. Hasan, S. Hore, M. Al Alim, R. Hore, and M. A. Ansary, "Numerical modeling of seismic soil-pile-structure interaction (SSPSI) effects on tall buildings with pile mat foundation," *Arabian Journal of Geosciences*, vol. 18, no. 1, Jan. 2025, doi: 10.1007/s12517-024-12155-4.

[5] R. Hore, M. Z. Hossain, S. Hore, M. Al Alim, R. Arefin, and M. A. Ansary, "A Comparative Seismic Study of Wrap-Faced Retaining Wall Embankment Using Sands of Bangladesh," *Iranian Journal of Science and Technology - Transactions of Civil Engineering*, vol. 49, no. 3, pp. 2857–2881, Jun. 2025, doi: 10.1007/s40996-024-01600-9.

[6] N. Srilatha, G. Madhavi Latha, and C. G. Puttappa, "Effect of frequency on seismic response of reinforced soil slopes in shaking table tests," *Geotextiles and Geomembranes*, vol. 36, 2013, doi: 10.1016/j.geotexmem.2012.10.004.

[7] M. Xiao, M. Ledezma, and C. Hartman, “Shake Table Test to Investigate Seismic Response of a Slurry Wall,” 2014. doi: 10.1061/9780784413272.120.
[8] M. Suzuki, N. Shimura, T. Fukumura, O. Yoneda, and Y. Tasaka, “Seismic performance of reinforced soil wall with untreated and cement-treated soils as backfill using a 1-g shaking table,” *Soils and Foundations*, vol. 55, no. 3, 2015, doi: 10.1016/j.sandf.2015.04.013.
[9] G. Madhavi Latha and A. Murali Krishna, “Seismic response of reinforced soil retaining wall models: Influence of backfill relative density,” *Geotextiles and Geomembranes*, vol. 26, no. 4, 2008, doi: 10.1016/j.geotexmem.2007.11.001.
[10] M. S. Arefin, A. Rahman Talukder, S. Hore, and R. Hore, “A Novel Study on Present Situation of Infrastructure of Water, Sanitation and Hygiene of Rural People in Bangladesh,” 2023. [Online]. Available: https://westerneuropeanstudies.com/index.php/4
[11] E. Çelebi, F. Göktepe, and A. J. Omid, “Seismic soil response of scaled geotechnical test model on small shaking table,” *Arabian Journal of Geosciences*, vol. 12, no. 2, 2019, doi: 10.1007/s12517-018-4197-8.
[12] G. Madhavi Latha and G. S. Manju, “Seismic Response of Geocell Retaining Walls Through Shaking Table Tests,” *International Journal of Geosynthetics and Ground Engineering*, vol. 2, no. 1, 2016, doi: 10.1007/s40891-016-0048-4.
[13] G. Madhavi Latha and A. M. Nandhi Varman, “Shaking table studies on geosynthetic reinforced soil slopes,” *International Journal of Geotechnical Engineering*, vol. 8, no. 3, 2014, doi: 10.1179/1939787914Y.0000000043.
[14] M. Kumar and S. S. Mishra, “Study of seismic response characteristics of building frame models using shake table test and considering soil–structure interaction,” *Asian Journal of Civil Engineering*, vol. 20, no. 3, 2019, doi: 10.1007/s42107-018-00114-w.
[15] S. Chen, B. Tang, K. Zhao, X. Li, and H. Zhuang, “Seismic response of irregular underground structures under adverse soil conditions using shaking table tests,” *Tunnelling and Underground Space Technology*, vol. 95, 2020, doi: 10.1016/j.tust.2019.103145.
[16] R. K. Reitherman, *Earthquakes and engineers: An international history*. 2012. doi: 10.1061/9780784410714.
[17] S. Hore, “Assessment of soil chemical characteristics in the context of Bangladesh: A comprehensive review,” *Community and Ecology*, vol. 2, no. 1, Sep. 2024, doi: 10.59429/ce.v2i1.6296.
[18] M. Sabermahani, A. Ghalandarzadeh, and A. Fakher, “Experimental study on seismic deformation modes of reinforced-soil walls,” *Geotextiles and Geomembranes*, vol. 27, no. 2, 2009, doi: 10.1016/j.geotexmem.2008.09.009.
[19] R. Hore(PhD), “Stability analysis of rainfall-induced landslides: A case study of a hilly area in Bangladesh,” *Earthquake*, vol. 1, no. 1, 2023, doi: 10.59429/ear.v1i1.95.
[20] R. Hore,PhD, “Systematic Approach of Earthquake Awareness Analysis in Bangladesh,” *Earthquake*, vol. 1, no. 1, Dec. 2023, doi: 10.59429/ear.v1i1.94.
[21] S. Chakraborty, R. Hore, A. M. Shuvon, M. S. Mazhar, and M. A. Ansary, “Dynamic Responses of Reinforced Soil Model Wall on Soft Clay Foundation,” *Geotechnical and Geological Engineering*, vol. 39, no. 4, 2021, doi: 10.1007/s10706-020-01665-z.
[22] R. Hore, S. Chakraborty, M. Ansary, A. Mahmud Shuvon, and M. Ahmed Ansary, “Experimental Investigation of Embankment on Soft Soil Under Cyclic Loading: Effect of Input Surcharges,” 2015, [Online]. Available: https://www.researchgate.net/publication/345904802
[23] A. M. Krishna and G. M. Latha, “Seismic response of wrap-faced reinforced soil-retaining wall models using shaking table tests,” *Geosynth Int*, vol. 14, no. 6, 2007, doi: 10.1680/gein.2007.14.6.355.