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Mitigation of Train-Induced Vibrations with Developed In-Filled Coir Composite Wave Barriers

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Abstract—The rapid urbanization and population growth in cities have led to the construction of buildings near train tracks. However, trains passing by these buildings generate ground vibrations that can potentially impact the structures and their foundations. Extensive research, including experiments, field studies, and finite element method analyses using computational software, is being conducted to identify effective mitigation techniques for reducing vibrations in buildings susceptible to train-induced vibrations. One crucial approach for vibration mitigation is the implementation of suitable wave barriers. This study focuses on evaluating the performance of in-filled coir composite barriers in isolating ground vibrations caused by trains. Coir composite, chosen as the fill material due to its favorable properties such as low density, low impedance, and low shear wave velocity, was utilized in the study. Prior to installing the coir composite barriers, a comprehensive field exploration was conducted to assess the site characteristics. The study findings highlight that the effectiveness of vibration mitigation depends on factors, including the type of infill coir composite barrier, and the distance between the building and the railway track. By considering these conditions, the most efficient vibration countermeasure can be determined. Overall, this study contributes to the understanding of the performance of in-filled coir composite barriers in reducing train-induced vibrations

Index Terms—Train induced vibration, Coir Composite barrier, Amplitude Reduction Ratio, Active isolation.

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1 INTRODUCTION

The problem of vibration isolation in soils has been extensively studied since the 1950s, focusing on various sources such as vibrating equipment, traffic, pile driving, and blasting. These ground vibrations propagate through the soil and can adversely affect nearby structures. Undesirable ground vibrations can lead to malfunctions in sensitive instruments or facilities housed within buildings, as well as causing continuous annoyance to occupants. With the expansion of cities through large-scale projects and increasing population, many buildings are now constructed near train tracks. Trains passing in close proximity to these buildings generate ground vibrations that pose a potential threat to the structures and their foundations. The vibrations induced by moving trains, particularly when in close proximity to high-rise buildings, can have destructive effects. The presence of high-rise buildings near railways is a consequence of both limited construction land and vertical expansion due to overpopulation. These high-rise buildings exhibit complex responses to different types of vibrations, especially those induced by moving trains in close proximity. Vibration mitigation techniques often referred to as vibration isolation or screening, involve the use of barriers to impede the propagation of surface waves. These barriers are designed to reflect, scatter, and diffract wave energy, thereby reducing the amplitude of the waves. By creating a geometric or material discontinuity in the wave field, barriers intercept incident waves and effectively minimize their amplitudes. Vibration screening techniques can be classified into two main categories based on the proximity of the barrier to the source of excitation. When the barrier is located close to the source, the isolation technique is referred to as active isolation. Conversely, if the barrier is placed remote from the source or near the target or site that requires protection, it is termed passive isolation In situations where other isolation techniques like machine base isolation are not feasible, the use of wave barriers can be an effective alternative for isolation. These barriers can take various forms, such as trenches (open or infilled), sheet piles, rows of solid or tubular piles, concrete walls, diaphragm walls, gas cushion screens, and more. The effectiveness of an isolation technique depends on the specific type of barrier employed. The selection of a suitable barrier is influenced by factors such as sub-soil characteristics, excitation frequency, and desired amplitude reduction level. Additionally, considerations of construction feasibility and cost must be taken into account when choosing an effective isolation measure.

Among the available options, open and infilled trenches are widely used due to their ease of construction and significant reduction in ground vibrations when appropriately designed. However, open trench barriers can present challenges such as sidewall instability, water-logging, and the potential risk of trapping humans or animals in the long run. In this regard, infilled trenches offer a preferable choice for long-term applications, as they avoid wall instability issues. The primary difference between these two types of barriers lies in the ability of an infilled trench to allow the passage of incident waves. An open trench acts as a point of material discontinuity in an otherwise undisturbed half-space, preventing the transmission of incident waves through it.

2 Literature Review

The pioneering work on wave barriers, specifically open trenches and infilled trenches, was conducted by Barkan [1]. This experimental investigation marked an important milestone in the field. Barkan's study revealed that the effectiveness of a barrier in screening vibrations increases with its depth and distance from the source of excitation. In a subsequent series of field tests, Woods [2] conducted both active and passive isolation using open trenches were examined. The study found that the most significant factor affecting screening effectiveness is the ratio between the depth of the barrier and the wavelength of the surface waves. In contrast, the breadth of the barrier played a minimal role in the isolation process. The research also demonstrated that achieving a desired amplitude reduction requires deeper trenches positioned at greater distances from the source. Based on the data obtained from these studies, guidelines were proposed for designing open trenches to achieve amplitude reductions of 75% or more. These guidelines provide valuable insights for engineers and practitioners in the design and implementation of effective wave barriers.

The 2D Finite Element Analysis (FEA) to model the movement of trains and assess their impact on nearby buildings was utilized by Hesami et al. [3]. The findings of the study revealed that increasing the speed of the train resulted in higher vibrations, while decreasing the speed of the train led to reduced vibrations. Additionally, the distance between the railway and the building was found to have an influence on the vibration levels. Based on their research, suggested a recommended distance of 18 meters between the railway and the building to mitigate vibrations effectively. Galvín et al. [4] investigated the impact of vibrations caused by high-speed train (HST) passage on both ballast and non-ballast tracks. They also examined the case of floating slab tracks. The study findings indicated that the critical speed for a ballast track is in close proximity to the Rayleigh wave velocity in the soil. Additionally, the research revealed that the floating slab system generates higher vibrations compared to the slab system on the track. These findings provide valuable insights into the behavior of different track types and their susceptibility to vibrations induced by high-speed trains. Kouroussis et al. [5] conducted a investigation using both experimental and numerical approaches to examine the vibrations caused by high-speed rail on different track support types: cutting, embankment, and at-grade sections. The study aimed to compare the vibration levels generated by these track support configurations. The findings of the study indicated that the embankment profile resulted in lower vibration levels compared to both the cutting and at-grade sections. This research provides valuable insights into the vibration characteristics of different track support types, aiding in the understanding and mitigation of vibrations associated with high-speed rail operations.

Thompson et al. [6] investigate the use of trenches as a ground vibration barrier and as a potential mitigation measure for frequency vibrations induced by surface railways. The research examines the performance of different trench configurations in reducing ground vibrations. The study concludes that rectangular open trenches exhibit the best performance, with depth being the most crucial parameter influencing their effectiveness. In contrast, the width of the trench has only a minor impact on its performance. The study also finds that barriers composed of soft fill materials are significantly less effective compared to open trenches. These findings provide valuable insights into the design and effectiveness of trench barriers for mitigating ground vibrations induced by surface railways. Persson et al. [7] studied traffic-induced ground vibrations and found that barriers can reduce vibrations numerically. They identified the depth of a trench and the elastic modulus of a solid back-fill material as crucial factors to consider. Additionally, they observed that the infiltration of water decreases the effectiveness of vibration reduction. The study also highlighted vibration amplification at longer distances from the vibration source. Feng et al. [8] used a three-dimensional finite element method (FEM) model to simulate and analyze ground vibrations caused by high-speed trains (HSTs). Their research focused on understanding the impact of HST vibrations and proposed mitigation strategies. The study provides valuable insights into the simulation and reduction of ground vibrations induced by high-speed trains. Xu et al. [9] proposed an information-theoretic approach for indirectly monitoring train traffic using building vibrations. Their method aimed to accurately calculate vibrations induced by moving trains near buildings. The study demonstrated the effectiveness of their approach, with promising results showing a high agreement rate of 93% in positive cases and 80% in negative cases when compared to field measurements. The paper contributes to the field of train traffic monitoring and highlights the potential of using building vibrations as an indirect monitoring method. Farghaly et.al [10] conducted a study on the dynamic response of a pedestrian tunnel subjected to train-induced vibrations from a four-track surface railway. They employed a 3D finite element method (FEM) model to simulate both the tunnel and the surrounding soil block. They focused on investigating the impact of different soil water contents on the dynamic behavior of the tunnel. The study provides information mainly into the train-induced vibrations and their effects on pedestrian tunnels, considering variations in soil water content.

Connolly et al. [11] conducted an analysis of technical reports on ground-borne noise and vibration from 1604 railway track sections in nine countries. The paper revealed that velocity decibels, vibration dose value, and peak particle velocity are commonly used methods for assessing ground-borne noise and vibration. They also found that the most frequently employed strategy for mitigating these issues is through active mitigation, which involves modifying the rail track structure. Passive solutions, on the other hand, were less commonly implemented. The findings highlight the prevalent assessment methods and mitigation approaches employed in the field of ground-borne noise and vibration in railway systems. Zoccali et al. [12] conducted a study focusing on the interplay between the length of trenches and the type of in-filled material, considering fixed observation points. They employed a finite element model calibrated using in-situ measurements. The study evaluated the effectiveness of various configurations by calculating the amplitude reduction index and analyzing vibration attenuation in both the time and frequency domains. Consistent with findings from other studies, they discovered that longer trenches provided better isolation effects. However, the extent of improvement appeared to be heavily influenced by the choice of in-filled material. This finding emphasizes the importance of considering material selection when optimizing vibration isolation strategies involving trenches. Celebi et al. [13] conducted experimental research on the isolation of building foundations near moving loads using open or in-filled trench barriers. They found that the dimensions of trenches should be assessed on a case-by-case basis for each building. The study concluded that the reduction effects of wave barriers, both in passive and active isolation cases are dependent on the frequency of the vibration source. This highlights the need to consider individual building characteristics and the frequency of vibration when determining the effectiveness of wave barriers for isolation purposes. Hasheminezhad [14] focused on reducing railway-induced vibrations using in-filled trenches with pipes. The research aimed to mitigate vibrations caused by railway traffic. The study explored the effectiveness of in-filled trenches with pipes as a mitigation measure. The findings contribute to the understanding of reducing vibrations induced by railways and provide insights into the use of in-filled trenches with pipes as a potential solution. Sanayei et al. [15] focused on the measurement and prediction of train-induced vibrations in a full-scale building. The research aimed to understand and accurately predict the vibrations caused by passing trains. The study involved both field measurements and predictive modeling. The findings contribute to the understanding of train-induced vibrations in buildings and provide insights into the measurement and prediction techniques for such vibrations in real-world structures. Ulgen et.al [16] conducted a study on the effectiveness of open, water-filled, and geofoam-filled trenches for isolation purposes. They investigated the impact of frequency, Rayleigh wavelength, and trench depth on the isolation performance. The study confirmed that a geofoam-filled trench can serve as an efficient wave barrier, providing effective isolation against waves. The findings highlight the potential of using Geofoam-filled trenches as a viable solution for wave attenuation and isolation.

Previous studies have primarily focused on investigating various sources of vibrations, such as train loading, sinusoidal loading, and impact loading. In the present study, a field case study was conducted near a railway track to examine the effectiveness of ground-borne vibration isolation. Coir composite infilled wave barriers were used in this study. The chosen site, located near a railway line, served as the testing ground to assess the wave barrier's efficacy in isolating train-induced vibrations. The main objective of the field case study was to analyze the ground motion resulting from the movement of trains in an open field. The following sections provide a detailed description of the conducted studies and their findings

3 METHODOLOGY

In the present field case study, the effectiveness of Coir Composite wave barriers in mitigating train-induced vibrations of waves was examined. The present study aimed to assess the efficiency of these barriers in reducing vibrations caused by passing trains. A field case study approach was utilized to evaluate the performance of Coir Composite wave barriers in real-world conditions. The findings from this study contribute to a better understanding of the potential of Coir Composite wave barriers as a viable solution for mitigating train-induced vibrations.

3.1 Development of Coir composite

Coir fibre, a readily available natural fibre in Kerala, India, was chosen as the base material for the development of an advanced vibration isolation material. By incorporating admixtures and applying appropriate treatment methods, the properties of the coir fibre can be enhanced. In this study, prevulcanised latex was used as a binding material for the coir composite. Prevulcanised latex refers to compounded latex where the rubber particle molecules are chemically cross-linked, resulting in vulcanization. Despite this chemical modification, the size, shape, and distribution of the rubber particles remain unchanged, and the latex retains its original fluidity and colloidal properties. For this study, a low viscosity adhesive compound specifically designed for spraying application (product code CL60MM20) was obtained from KA Prevulcanised Latex Private Limited, located in Nagercoil, Tamilnadu, India. This particular latex product is suitable for manufacturing multilayer coir products.

The development of the Coir Composites used in this study is described in the following section. The material properties of these composites were determined in the Geotextile testing laboratory at the College of Engineering Trivandrum.

In this study, the coir fibre obtained from the coir industry was processed using machinery to prepare the coir composite. The physical and mechanical properties of the coir fibre were tested in the laboratory according to Indian standards and ASTMD4533.

For the spraying application, natural pre-vulcanized latex of grade CL60MM20 was used. A non-woven coir geotextile was prepared using the needle felt method, and the natural pre-vulcanized latex was sprayed over it. The weight ratio of latex to coir was set at fifty percent in this study. The coir composite developed in this study is referred to as the Needle Felt Coir Latex Composite (NFCLC50), where "50" signifies the latex content added to the coir composite material, accounting for 50% of the total mixture. The prepared coir-latex composite is illustrated in Figures 1.

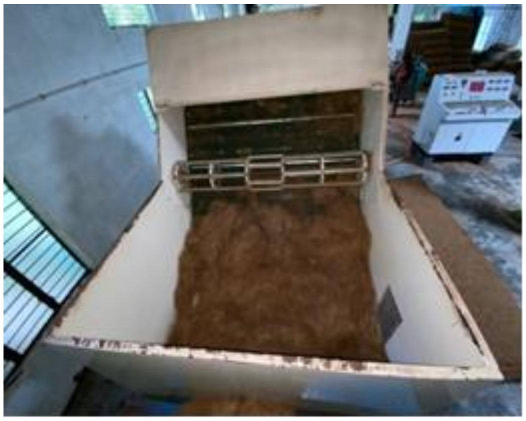

Figure 1: Laying of the Coir fibres

Figure 2: Latex is uniformly sprayed onto the mats

Figure 3: Developed Needle felt Coir-Latex Composite (NFCLC50)

The production process involved several steps. Firstly, the air-dried bale of coir fibre was opened up and cleaned using a willowing machine. The coir fibres were then fed into an automatic fibre feeder unit and subjected to the carding process. The needle punching machine, equipped with a reciprocating needle board with stripper plates and bed plates, was used. The web was punctured multiple times by a battery of needles to reorient and interlock the fibres, resulting in the formation of a continuous sheet. A non-woven needle-punched coir geotextile with a weight of 1000 GSM and a thickness of 10 mm was obtained.

The coir geotextile was cut into 1.50m long and 1.00m wide pieces using a cutting machine. These pieces were layered to achieve a thickness of 150 mm. The amount of latex applied was determined based on the weight of the coir geotextile, following 50% latex to coir weight ratio. The pre-vulcanized latex was evenly sprayed onto both sides of the geotextile using a sprayer with a pressure of 0.5 kg/cm^2. After 15 minutes of sun-drying, the coir latex composite was compressed to facilitate the penetration of the sprayed latex. This process resulted in the formation of a Coir Composite wave barrier

3.2 Material Properties of Coir Composite

The physical properties of NFCLC50, including thickness (t), density, and mass per unit area (m), were determined through testing and are presented in Table 1.

Table 1: Physical Properties of NFCLC50

Property	*Unit*	*Value*
Thickness	mm	20.11±0.73
Mass per unit area	g/m^2	3328.94±46.30
Density	kg/m^3	146.169±7.11

The Wide Width Tensile Strength Test was performed on NFCLC50 to determine its mechanical properties, such as tensile strength, tangent modulus, modulus of elasticity (E), and Poisson's ratio (μ), and the results are shown in Table 2.

The wave velocity and impedance of NFCLC50 were calculated based on the test results. The thickness of the composites was determined in the laboratory according to IS: 13162-3 (1992) standards, and the mass per unit area was calculated in grams per square meter (GSM) following IS: 15868 (Part 1 to 6):2008 guidelines. The evaluation of the properties of the NFCLC50 specimen was based on the Minimum Average Roll Value (MARV), which represents the average of the samples plus or minus two times the standard deviation.

Table 2: Mechanical properties of NFCLC50

Properties	*Symbol*	*Unit*	*NFCLC50*
Tensile strength	σ	kN/m	56.03 ± 4.17
Initial tangent modulus	E_t	kN/m	86.48 ± 22.39
Modulus of elasticity	E	MN/m^2	4.16±1.02
Strain at failure	ε	%	19.28±3.92
Poisson ratio	μ	-	0.21
Shear wave velocity	V_s	m/s	34.43
Rayleigh wave velocity	V_R	m/s	29.74

The Wide Width Tensile Strength Test, conducted on 10 sample specimens according to IS 13162.5:2015, generated a stress-strain graph and the results including tensile strength and initial tangent modulus are presented in Table 2.

To determine the Poisson's ratio of NFCLC, the lateral strain of the specimen was measured during the Wide Width Tensile Test. Three markings (A, B & C) were made on the specimen at specific positions (one-fourth, two-fourths, and three-fourths of the gauge length). A video camera (Nikon D3300 Digital SLR Camera) placed on a tripod was used to capture the lateral movement of the markings. The camera recorded at a speed of 24 frames per second and was positioned at a horizontal distance of 120cm from the sample as presented in Figure 4. The video footage was processed using Adobe Premiere Pro 2020 software to extract frames and determine the lateral thickness of the specimen for each load increment. Automeris Software was used to measure the lateral thickness of NFCLC50. Poisson's ratio was calculated by plotting the lateral and longitudinal strain, and the values are presented in Table 3.

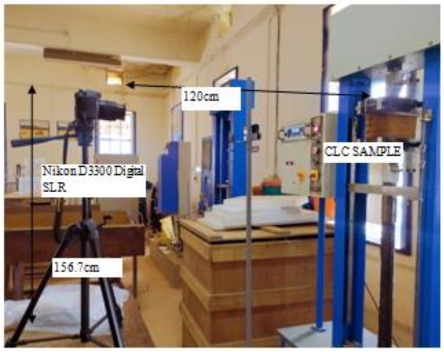

Figure 4: Typical experimental setup for the Poisson's ratio test

3.3 Characteristics of the site for field case study

For the real-time case study, the CSIR Industrial Estate Road located near Thiruvananthapuram, Kerala was selected as the proposed test location as presented in Figure 5. This site, situated near a railway line, was chosen to assess the effectiveness of a wave barrier in isolating train-induced vibrations. The primary objective of the field case study was to analyze the ground motion generated by the passage of trains in an open field. To begin with, a site investigation was conducted to determine the characteristics of the soil in the vicinity. The trench was located at a distance of 5.50 meters from the railway line, while the residential buildings were situated 8.55 meters away from one side of the railway line, as illustrated in the figure 6. The properties of the soil were determined by collecting samples from the site and conducting tests in accordance with the IS methods. The results of these tests are presented in Table 3

Figure 5: Site Location: CSIR Industrial Estate Road, Thiruvananthapuram-Kerala

Table 3 Properties of soil at the site selected

Parameters	Symbol	Unit	Value
Soil classification	-	-	Silty Sand
Water content	w		16.1
Specific Gravity	G	-	2.73
Liquid Limit	W_L	%	51.14
Plastic Limit	W_P	%	36.34
Plasticity index	I_p	%	14.80
Density	γ	kN/m^3	25.69
Angle of internal friction	φ	degrees	36
Cohesion	C	kN/m^2	2.94

3.4 Field Procedure

The field experiments were conducted to study the propagation of waves through the ground and to assess the effectiveness of the Coir Composite in mitigating vibrations. Accelerometers were strategically placed on the ground at different distances from the source of train-induced vibrations, and the resulting ground vibrations were measured. The collected acceleration data from the field case study were subsequently analyzed to evaluate the performance of the coir composite in reducing vibrations.

A trench was constructed at a distance of 5.50 m from the railway line, and filled with NFCLC50 material. Three accelerometers, labeled A1, A2, and A3, were placed at distances of 4.90m, 6.25m, and 8.65m from the edge of the railway line, respectively, to measure acceleration amplitudes. The positions of A2 and A3 were located 0.6m before and after the trench, respectively. These accelerometers were connected to a data logger and their readings were recorded using the DEWESoftX software. The layout of the test setup in the field is illustrated in Figure 7.

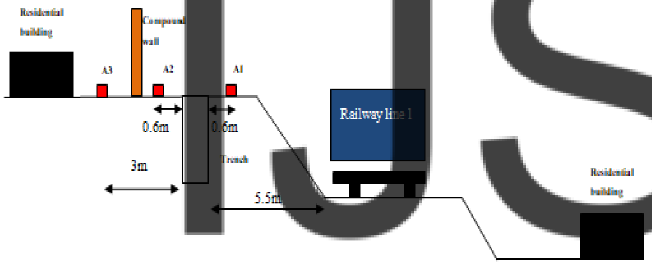

Figure 6: Layout of test arrangement of Field case study (sectional view)

The study used vibrations from two trains as sources, namely the Nagercovil Kottayam Express (16366) and the Chennai Egmore Kollam Anantapuri Express (16723). The vibrations of each train were monitored during its back and forth journey (four number of train movement). Figure 7 shows the test arrangements of wave barriers, the source and acceleration measuring system. The ground vibration due to the movement of express train near the residential building was studied in the no trench case, while the other three trains movement were studied with an infilled NFCLC50 barrier. Vibrations were measured during a 16sec period corresponding to the duration of the train movement. The wave barrier's effectiveness was evaluated by measuring the acceleration amplitudes using accelerometers and comparing the results. The amplitude reduction ratio (ARR) was then calculated by dividing the peak acceleration amplitude (PAA) measured after the wave barrier by the amplitude measured before the barrier

Figure 7: Test set up with source of vibration.

According to Woods [2], a wave barrier is considered adequate if it achieves a maximum amplitude reduction ratio of 0.25. A lower ARR value indicates a more efficient wave barrier. The performance of the Coir Composite wave barrier was assessed using the following equations.

Amplitude Reduction Ratio (ARR)

$$=\frac{\text{Peak Amplitude Accelration after barrier}(A2)}{\text{Peak Amplitude Acceleration before barrier}(A1)} \qquad \text{Eqn (1)}$$

$$\text{Efficiency of a barrier} = (1-\text{ARR})\times 100 \qquad \text{Eqn (2)}$$

4 Results and Discussions

Ground vibrations were measured at three pickup points: A1 (4.90m), A2 (6.25m), and A3 (8.65m) from the railway line. Figures 8 to 11 depict the acceleration time history for A1, A2, and A3 in four express train movements near a residential building. The average peak ground acceleration (PGA) for all express trains was 0.036g at A1.In Figure 8, representing the no trench case for Express train 1, the PGAs at A1, A2, and A3 were 0.036g, 0.029g, and 0.020g, respectively. Figure 9 shows the PGA values for the NFCLC50 wave barrier case for Express train 2, with values of 0.035g, 0.013g, and 0.011g at A1, A2, and A3, respectively. The peak ground acceleration (PGA) values from Figures 8 to 11 are summarized in Table 4.

Table 4. Peak Ground Acceleration obtained for field case

Train	*Trench condition*	*PAA* (g)			*ARR*	
		A1	*A2*	*A3*	*A2*	*A3*
1	Without trench	0.036	0.029	0.020	0.815	0.548
2	Without trench NFCLC50	0.035	0.013	0.011	0.373	0.324
3		0.037	0.014	0.010	0.380	0.265
4		0.037	0.012	0.009	0.329	0.241

Without a trench, the calculated ARR values for A2 and A3 were 0.815 and 0.548, respectively. However, with the implementation of the NFCLC50 barrier, the average ARR values decreased to 0.360 and 0.276, highlighting the effectiveness of the NFCLC50 material as a vibration mitigation measure.

Efficiency comparisons were made between the no trench and NFCLC50 cases. In the no trench scenario, the efficiencies of A2 and A3 relative to A1 were 18.54% and 45.22%, respectively. With the NFCLC50 wave barrier, the efficiencies of A2 and A3 relative to A1 improved to 63.95% and 72.35%, respectively.

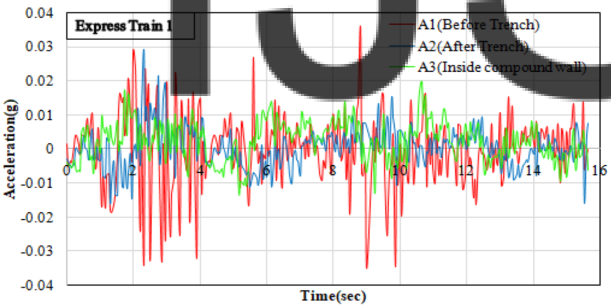

Figure 8: Acceleration time history graph for no trench case (Express Train 1)

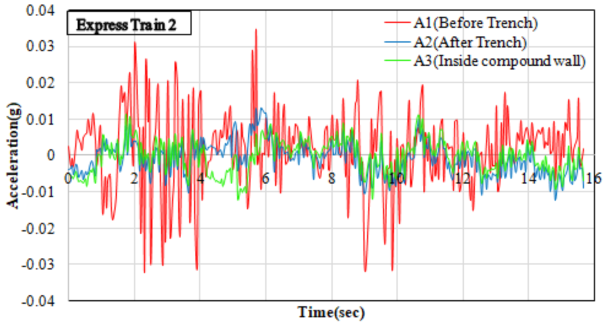

Figure 9: Acceleration time history graph for NFCLC50 (Express Train 2)

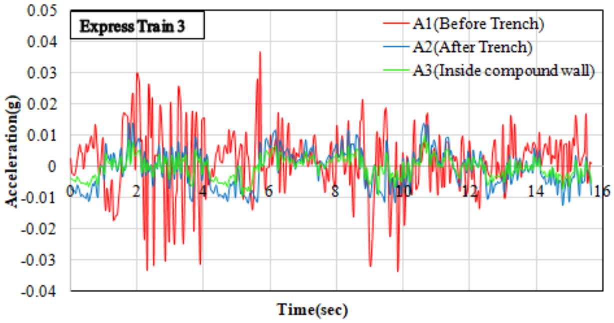

Figure 10: Acceleration time history graph for NFCLC50 (Express Train 3)

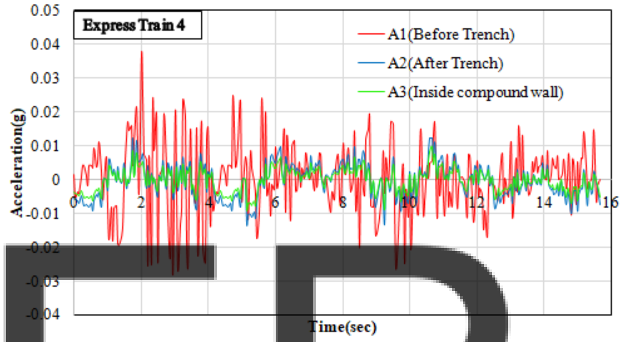

Figure 11: Acceleration time history graph for NFCLC50 (Express Train 4)

5 Conclusions

The efficiency of the NFCLC50 barrier in attenuating ground vibrations caused by train movement was studied through a field case study. Based on these investigations, the following conclusions were drawn:

- The development of NFCLC50 material involved the creation of a coir-latex composite using coir fibers and natural pre-vulcanized latex. The material composition consisted of 50% latex content by weight of the coir, which was then sprayed onto the non-oven coir geotextile. The material properties of NFCLC50 were evaluated, and it was found that the material is highly suitable for use as a wave barrier.
- The properties of the NFCLC50 barrier, specifically the modulus of elasticity (4.16 MN/m²), Poisson's ratio (0.21), and density (146.169 kg/m³), play a significant role in achieving ground vibration reduction.
- NFCLC50 is an effective and environmentally friendly solution for mitigating ground vibrations. Its sustainability is attributed to the utilization of coir, a natural and renewable fiber, making it a viable alternative to synthetic materials that can have

negative environmental consequences. Although the percentage of latex used and its vulnerability to degradation or moisture absorption over time may impose certain limitations on its effectiveness, NFCLC50 still offers greater stability compared to open trench methods. As a result, it serves as an efficient barrier for isolating ground-borne vibrations.

- The field case study presented a successful reduction of vibrations caused by train movement using an NFCLC50 barrier. The study effectively demonstrated the efficiency of the NFCLC50 barrier in reducing vibrations. In particular, the implementation of the NFCLC50 barrier resulted in efficiencies of 63.95% and 72.35% for A2 and A3, respectively, when compared to A1.

Data Availability statement

The author affirms that the data supporting the findings presented in this paper are accessible within the article itself. Upon request, the corresponding author can provide the raw data, including any data not included in the article.

Conflict of interest

The authors declare that they have no conflicts of interest that could potentially influence the findings or interpretation of this publication

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