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Centrifuge Model Testing of Vibration Isolation Effect of Foam Concrete-Sand Composite Barriers for Metro Tunnels

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ABSTRACT: Traffic-induced vibration has become a growing concern due to its environmental impacts in densely populated urban areas. In particular, vibrations generated by subway operations can adversely affect residents' daily life, industrial activities, and high-precision experiments, highlighting the need for effective mitigation measures. To achieve a balance between cost efficiency and vibration reduction performance, this study proposes the use of composite barriers made of foam concrete and sand mixtures at varying proportions as vibration isolation measures. These barriers are positioned 10 cm away from the metro tunnel, and their performance is evaluated through centrifuge modeling tests. Four mixture ratios were investigated: one-third foam concrete mixed with two-thirds medium sand, one-half foam concrete mixed with one-half medium sand, two-thirds foam concrete mixed with one-third medium sand, and full foam concrete filling. The objective is to identify the optimal configuration for mitigating vibrations induced by metro operations. The results indicate that vibration isolation effectiveness gradually decreases as the proportion of foam concrete declines. The fully foam concrete-filled barrier achieves the best vibration isolation performance, with a vibration levels reduction of 7.8 dB before and after isolation. Notably, the barrier with 2/3 foam concrete filling retains approximately 86% of the vibration isolation effectiveness of the fully filled configuration, offering a promising compromise that ensures high isolation efficiency while significantly reducing project costs.

1 INTRODUCTION

Vibration caused by metro operation and its impact on surrounding environments have become increasingly concerning with the expansion of underground structures in global cities. In response, scholars(Leng et al., 2024; Liu et al., 2024; Zhang et al., 2025) have conducted extensive research on subway vibration mitigation, proposing various isolation measures.

The principle of vibration isolation system is to set up a barrier layer between the vibration source and the protected structures(Wang et al., 2022). This layer absorbs wave energy, thereby mitigating vibrations. Consequently, the selection of barrier materials is critical. High damping properties and favorable acoustic characteristics can significantly enhance a barrier's vibration isolation performance.

Foam concrete, characterized by its low density, light weight, acoustic absorption, and vibration resistance, is considered a highly desirable isolation material(Raj et al., 2019). For instance, Zhao et al. (2018) compared the vibration isolation performance and effectiveness of rubber and foam concrete, while Ma et al. (2019) investigated its mechanical properties through compression and direct shear tests. Their findings indicate that these properties are significantly influenced by density, with the material exhibiting high compressibility and effective vibration damping. Furthermore, Azaman et al. (2017) conducted an in-depth study on polypropylene-foam concrete floor slabs, demonstrating the superior vibration isolation capacity of foam concrete in building applications.

A review of the existing literature reveals a lack of comprehensive studies on vibration mitigation specifically for metro operations and limited practical guidance on effective isolation measures. Therefore, this study experimentally investigates the performance of vibration isolation barriers constructed with foam concrete and sand. To ensure realistic stress conditions and improve experimental fidelity, centrifuge modeling was employed to replicate the in-situ stress levels of prototype strata. The vibration damping effects of different material combinations were analyzed to identify an optimal isolation configuration and provide a valuable reference for engineering applications.

2 EXPERIMENTAL STUDY

2.1 Experimental equipment

The experiments were carried out on the TLJ-150 centrifuge at Tongji University. The dimension of the model box used in this test is 900 mm× 350 mm× 700 mm (length × width × height). To reduce the impact of boundary conditions on the test, the 5 -cm thick polystyrene plates should be installed on all four sides and the bottom of the model box(Liu et al., 2018). The arrangement is shown in the figure 1.

In this test, the loading method is designed to control the vibration frequency within the range of actual operational frequencies. Accordingly, the similarity ratio governing the loading time is of primary concern. The geometric similarity ratio is set at 1:100, while the density and elastic modulus similarity ratios are both 1:1. Based on these parameters, the time similarity ratio is derived as 1:100.

Figure 1. TLJ-150 centrifuge.

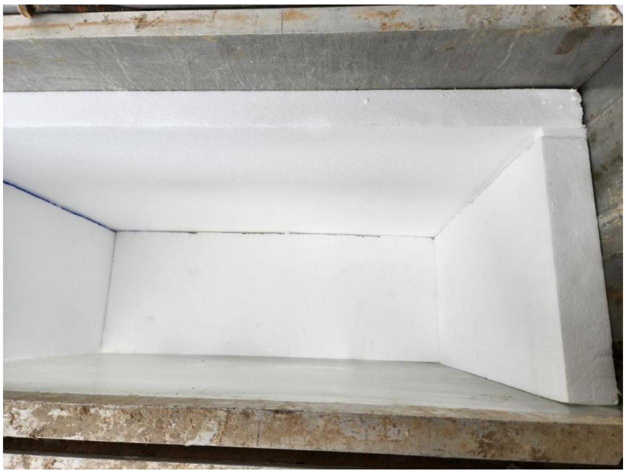


Figure 2. Boundary for vibration absorption.

2.2 Experimental preparation

2.2.1 Sample soil and station model

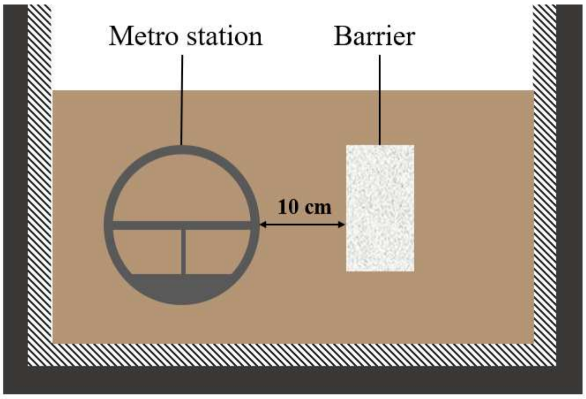
The sample soil consists of remolded Shanghai four-layer soil, i.e., gray silty clay. It was obtained through field sampling. The detailed material parameters are shown in Table 1.

Micro-concrete was chosen for the preparation of the station model with a diameter of 30 cm and a thickness of 1.2 cm.

Table 1. Sample soil parameters.

Parameters	Value	Unit
Unit weight	18.7	g/cm^3
Modulus of elasticity	14.67	MPa
Internal friction angle	26.8	°
Cohesion	16.8	kPa
Poisson ratio	0.3	

(a) Station model sample preparation.



(b) Relationship between vibration isolation barrier and Metro station.

Figure 3. Station model.

2.2.2 Design for operating conditions

To test the vibration isolation performance of foam concrete and medium sand filled within diaphragm wall structure with a uniform-sized hollow block, four types of filling schemes were designed in Table 2.

Table 2. Different filling ratios of foam concrete and medium sand.

Conditions	Foam concrete	Medium sand
I	1/3	2/3
II	1/2	1/2
III	2/3	1/3
IV	1	0

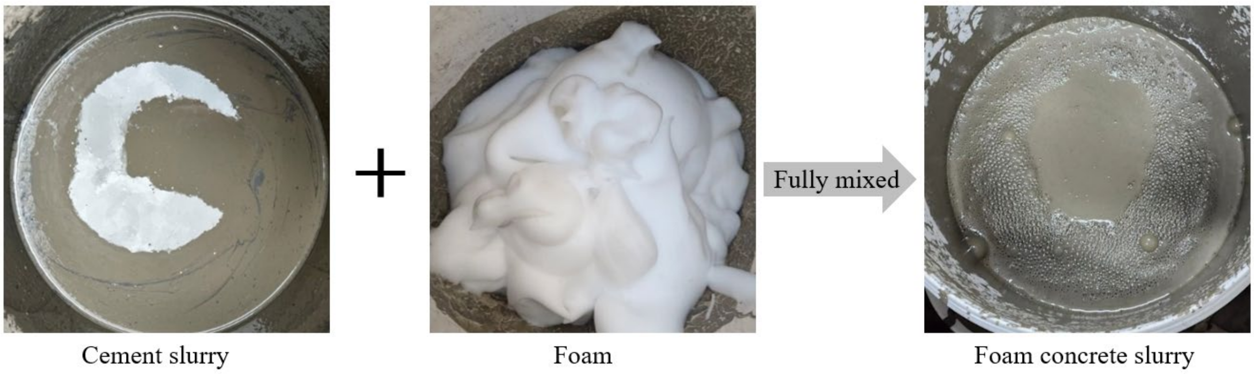
2.2.3 Preparation of foam concrete

Based on several tests, the parameters for the foam concrete mix selected for the experiments are shown in Table 3.

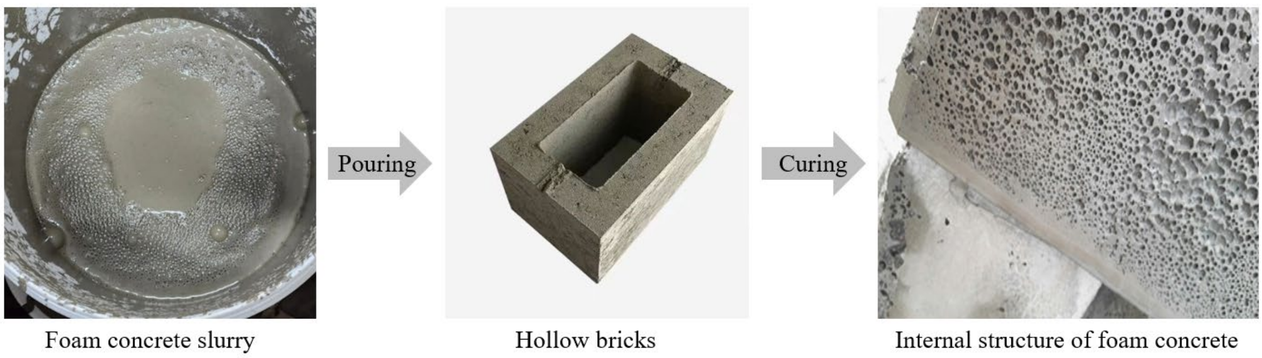
Table 3. Parameters for foam concrete.

Materials	Volume(kg/m^3)
Cement	600
Foaming agent	2
Thickening agent	0.3
Superplasticizer	1.8
Water	300

According to the specified mix ratio, cement, thickener, and stabilizer are measured sequentially and mixed thoroughly with the pre-measured water (excluding that necessary for the foaming agent). Dilute the foaming agent with water, then put it into a small foaming machine until it becomes stable. The preparation process is shown in Figure 4. Based on the filling scheme designed for each operating condition, the mixture is poured into precast C30 hollow bricks with a size of 190×120×120 mm. The entire structure is cured for 28 days to ensure the internal structure is fully formed. The vibration isolation barrier functions by intercepting vibrational wave energy along the propagation path. When waves encounter the barrier, they are reflected and diffracted, reducing the energy transmitted to the protected area. In this study, the barrier is positioned close to the tunnel to effectively intercept the propagation path of the primary waves.



(a) Preparation process of foam concrete.



(b) Preparation process for vibration isolating walls.
Figure 4. Production process.

Notably, even if the barrier height is less than the tunnel diameter, significant vibration attenuation can still be achieved when the barrier is properly installed. However, full-height barriers may not always be feasible due to cost or space constraints. To address this limitation, the proposed hollow-block vibration isolation barrier offers a practical compromise between isolation performance and constructability.

2.2.4 Loading method

First of all, the completed vibration isolation wall was embedded into the soil layer. The arrangement was shown in Figure 5. The soil and vibration-isolation wall were consolidated under 100 g to restore the stress state of field soil. The foam concrete vibration-isolation wall is located 25 cm from the center of the subway station.

Figure 5. Vibration isolation wall arrangement.

Since traffic-induced vibrations are primarily low-amplitude, the resulting strains in foundation soils typically remain within the elastic range. Therefore, it is essential to ensure that the experimental model operates within the elastic regime to accurately simulate the relevant phenomena. In this test, the excitation force was controlled by varying the input voltage amplitude. A 1000 mV excitation voltage was used to apply a frequency sweep signal ranging from 0 to 100 Hz to the model over a duration of 50 s. This 50 s window corresponds to the time period during which an actual subway train approaches and then completely clears the station structure. The loading points are shown in Figure 6, while the applied excitation time-domain and frequency-domain plots in Figure 7.

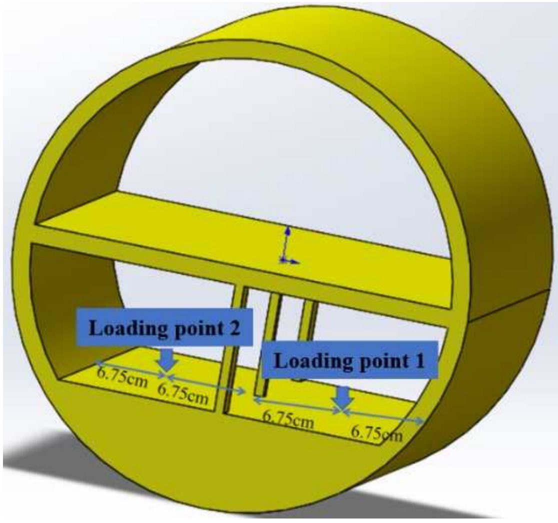
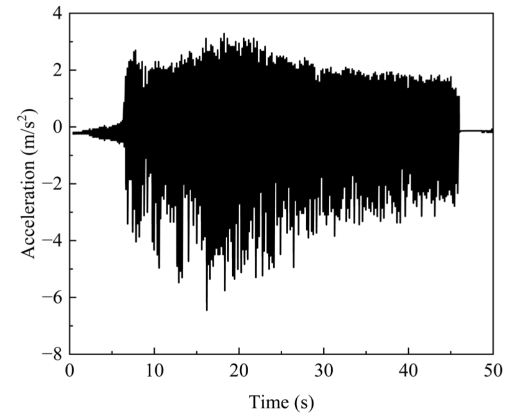
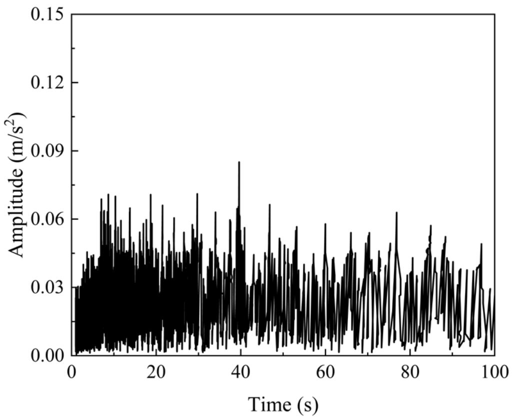


Figure 6. Location for excitation force application.



(a) Time-domain diagram for excitation.



(b) Frequency-domain diagram for excitation.
Figure 7. Loading curve.

3 RESULTS AND DISCUSSIONS

3.1 Comparison of Z-vibration levels at different filling ratios

The acceleration responses were compared for the cases without an isolation wall and with isolation walls filled with foam concrete at ratios of 1/3, 1/2, 2/3, and full capacity. Using the Z-vibration level evaluation method, the isolation effectiveness under various conditions was assessed, with the comparison results presented in Figure 8. As can be seen from the figure, the vibration isolation performance improves progressively as the foam concrete filling ratio increases. In particular, when the hollow bricks are fully filled with foam concrete, the vibration isolation wall achieves the best performance , with a vibration level reduction of 7.8 dB compared to the case without a barrier. When 2/3 of the hollow brick volume is filled with foam concrete, the vibration isolation effect reaches 6.7 dB, which is only 1.1 dB lower than that achieved with full filling. This indicates that the 2/3 filling configuration retains high isolation effectiveness while offering potential material savings, underscoring its viability as a cost-effective alternative.

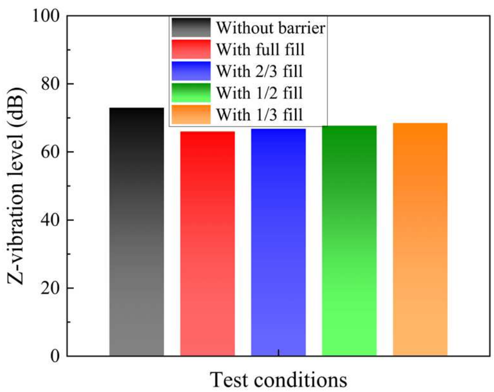


Figure 8. Z-vibration level comparison.

3.2 Comparison of power spectral density at different filling ratios

To enable a more detailed comparisons of vibration attenuation effects for different materials, the attenuated time-domain signals are transformed into frequency-domain, allowing for an analysis of attenuation characteristics across various frequency bands. Figure 9 presents the power spectral density (PSD) as a function of frequency for the scenario without an isolation barrier and for four different filling ratios of the foam concrete isolation wall. As shown in the figure, regardless of the proportion of foam concrete used, the vibration isolation barrier consistently exhibits a significant attenuation effect, particularly in the frequency ranges of 30–60 Hz and above 80 Hz. For the barrier fully filled with foam concrete, the average PSD reduction before and after the wall is 7.8 dB, with a maximum reduction of 20.4 dB observed at approximately 85 Hz. At a filling ratio of 2/3, the average PSD reduction is 6.7 dB, with a maximum reduction of 18.05 dB. For the 1/2 filling ratio, the average reduction is 6.1 dB, and the maximum reduction reaches 18.24 dB. When the filling ratio is 1/3, the average PSD reduction is 5.5 dB, with a maximum reduction of 19.24 dB.

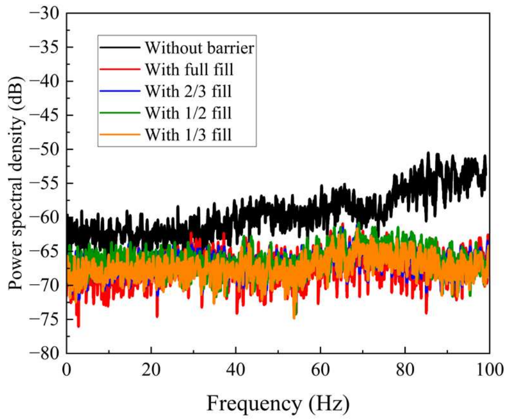


Figure 9. Power spectral density frequency domain plots for different filling ratios.

4 CONCLUSIONS

Based on centrifuge model tests, this study designed four operating conditions to investigate the performance of a foam concrete-sand composite isolation wall. Subsequently, the influence of different filling ratios on the wall's vibration isolation effectiveness was analyzed. Finally, the Z-vibration level and power spectral density were used to evaluate the wall's performance across operating conditions, leading to the following conclusions:

(1) Filling hollow bricks with foam concrete forms a vibration-isolation barrier, effectively reducing vibration responses within soil layers.

(2) The foam concrete-sand composite vibration-isolation barrier effectively overcomes performance limitations within the 70-80Hz frequency range.

(3) At a 2/3 foam concrete filling ratio, the composite barrier achieves vibration isolation performance comparable to a fully filled barrier while maintaining stable high-frequency isolation.

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