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VIBRATION MITIGATION BEHAVIOR OF BAMBOO-FILLED BARRIERS

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ABSTRACT

Ground-borne vibrations consistently challenge nearby buildings, impacting their serviceability adversely. This study explores the potential of using sustainable and environment-friendly materials as an effective solution for mitigating such vibrations using bamboo-filled barriers. A series of tests were conducted to investigate the vibration mitigation behavior of both bamboo-filled barriers (*BB*) and open barriers (*OB*). Various barrier configurations were used in the current study to strengthen the investigation. The influence of trench location, barrier type, and volume of the filler material on the screening response of trenches is extensively investigated using large-scale tests. In addition, the efficacy of the barrier in mitigating vibrations at measurement locations along the angular lines is explored. The results demonstrate that both barriers exhibit satisfactory performance in vibration mitigation, with their efficacy increasing notably at higher frequencies. Barriers with a lower volume of filler material exhibited superior vibration mitigation compared to those with a higher volume. Furthermore, practical insights into the installation process and precautions for installing *BB* panels are provided, offering valuable guidance for field engineers in real-world applications.

KEYWORDS: Bamboo-Filled Barriers; Open Barriers; Vibration Attenuation; Vibration Screening; Wave Propagation**.**

INTRODUCTION

In recent years, the intensification of urban expansion has brought industrial activities closer to critical infrastructure, heightening concerns about the impact of vibrations on structural integrity and performance. Such vibrations, often generated by heavy machinery, transportation networks, and construction activities, can lead to long-term structural damage and reduced service life (Ahmad et al., 1996; Surapreddi and Ghosh, 2022a; Das and Ghosh, 2024a; Singh et al., 2024). Addressing the detrimental effects of ground-borne vibrations requires effective mitigation strategies, particularly when directly reducing vibrations at their source is not feasible. A promising solution is the implementation of wave barriers, which are designed to intercept propagating waves, thereby reducing the vibrations beyond the barrier. Previous studies explored the vibration mitigation capabilities of wave barriers with various in-filled materials, such as concrete walls (Kattis et al., 1999; Celebi et al., 2009), soil-bentonite (Ahmad and Al-Hussaini, 1991; El Naggar and Chehab, 2005; Celebi et al., 2009), wave impeding blocks (Celebi and Goktepe, 2012), sheet piles (Gao et al., 2006), geofoam (Alzawi and El Naggar, 2011; Majumder and Ghosh, 2016; Bose et al., 2018; Jauhari et al., 2023, 2024), and sand-rubber mixtures (Mahdavisefat et al., 2018). Despite the effectiveness of these materials in certain applications, many fail to significantly enhance the stability of the barriers or meet the sustainability requirements. Additionally, the high cost and complexity of installation have limited their widespread adoption in urban settings. To address these challenges, this study explores the potential of bamboo as an innovative, eco-friendly in-filled material for wave barriers. By investigating the vibration mitigation capabilities of bamboo through a series of field experiments, this research aims to provide insights into its viability as a sustainable alternative for vibration mitigation in urban environments. While previous studies examined the vibration screening behavior of bamboo-filled barriers (Kumar and Ghosh, 2020; Surapreddi and Ghosh, 2023), the vibration reduction characteristics along angular lines have not been adequately discussed. Accordingly, this paper extensively explores the vibration mitigation behavior of bamboo-filled barriers (*BB*) through a series of field-scale experiments.

TESTING PROGRAM

Experiments were conducted at the geotechnical field laboratory located at the Indian Institute of Technology Kanpur. *GPS* coordinates of the test site are N26°30’59.0892” (latitude) and E80°13’51.6888” (longitude) [Surapreddi and Ghosh, 2023]. A detailed geotechnical investigation was performed by Surapreddi and Ghosh (2022b, 2023), Das and Ghosh (2024b), and Das et al. (2024) at the same location used in the present study. The geotechnical properties of the soil are presented in Table 1, where f_i is the input frequency.

Table 1: Mechanical properties of the soil (After Surapreddi and Ghosh, 2022b)

Property	**Value**
Specific gravity	2.62
Bulk density (kg/m^3)	1800
Poisson’s ratio	0.30
Shear wave velocity (m/s)	225
Rayleigh wave velocity (m/s)	208
Rayleigh wavelength (m) at f_i = 2700 rpm	4.63
Modulus of elasticity (MPa)	237
Classification (USCS)	CL

The site was cleared and leveled before marking the measurement locations (*ML*s) where the responses were measured. The precise establishment of these *ML*s was achieved using a total station. The total station was used to establish the coordinates of the farthest *ML*s from the source of vibration. Wooden pegs were inserted into the ground to mark the locations of various *ML*s. In addition, the location of the intermediate *ML*s was verified using the total station to ensure the accuracy of the survey. After completing the site survey, the dynamic load was applied to the foundations, and the responses were recorded at different *ML*s. The *ML*s were marked in the field, as shown in Figure 1.

Vibrations were generated by applying a vertical dynamic load using a Lazan-type mechanical oscillator installed on top of a square foundation, as shown in Figure 2. It is worth noting that the force generated by the oscillator is frequency-dependent. For testing purposes, an eccentric force setting of 0.134 N-sec^2 was used. The load configuration details of the mechanical oscillator for this setting are presented in Table 2. Following the recommendations of Surapreddi and Ghosh (2022b), frequencies greater than 1500 rpm were used for the current investigation. The design of the mechanical oscillator ensures that its centroid is aligned with the centroid of the reinforced foundation. The oscillator was properly clamped to the foundation to prevent any lateral movements. A square foundation having a width and height of 0.75 m and 0.45 m, respectively, was used for the experiments. Typical reinforcement details for the square foundation are presented in Figure 3.

Table 2: Loading configuration of the mechanical oscillator

Input frequency (rpm)	**Applied force (kN)**
1500	3.3
1800	4.8
2100	6.5
2400	8.5
2700	10.7

Fig. 1 Site survey for marking the measurement locations in the field

Fig. 2 Square foundation with a mechanical oscillator mounted on top

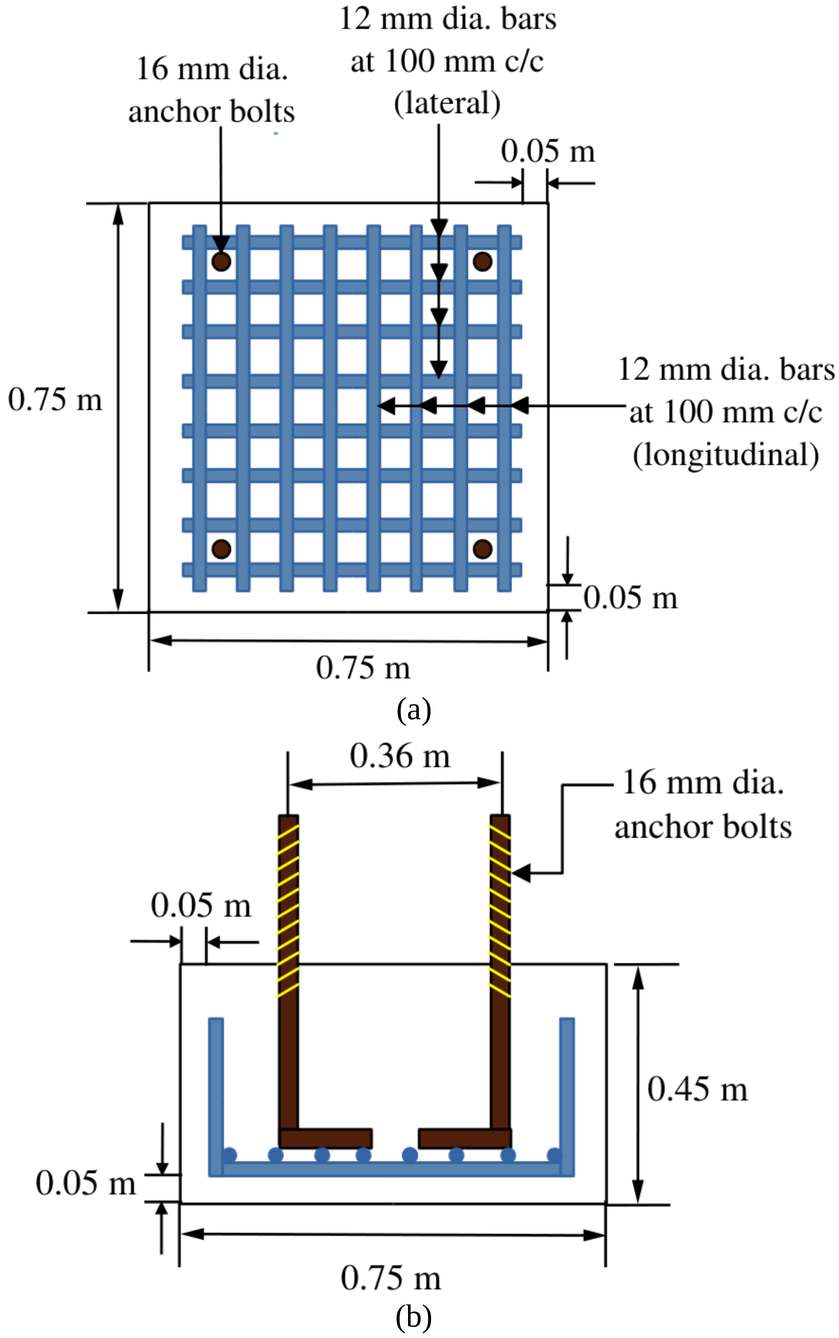


Fig. 3 Reinforcement details for the square foundation: (a) top view and (b) cross-sectional view

Extensive studies were conducted to determine the vibration mitigation behavior of different barriers. Sensors were placed at an equal spacing of 1.5 m at different *ML*s to capture the vibration responses. The responses were recorded at *ML*s located along the centerline of the footing and the angular lines on either side of the footing, as shown in Figure 4. The performance of different wave barriers such as open barriers (*OB*) and bamboo-filled barriers (*BB*) was evaluated, as shown in Figure 5, where *h* and *w* are the height and the width of the barrier, respectively.

The bamboo-filled panels were prepared according to the trench dimensions so that the *BB* panels could be easily installed. The bamboos used in this study belong to the Dendrocalamus strictus family of bamboos. Defect-free bamboo culms were used for the preparation of the *BB* panels. To prevent damage to the trench walls and facilitate smooth installation, a chain and pulley apparatus was used, allowing the bamboo panels to be lowered gently into place. Figure 6 shows the installation of the *BB* panels in the field. During the installation, careful attention was given to removing loose stones, protruding clods of earth, or pockets of unstable materials that could pose a hazard to workers or compromise the stability of the barrier. Tools and materials were kept away from the barrier edges to prevent accidental falls into the trench, and heavy machinery, such as excavators, was prohibited from operating near the barrier sides. The influence of the trench location was investigated using the schematic shown in Figure 7, where T_l is the trench location and S_m represents the distance between the measurement location (*ML*) and the centerline. Similarly, X_m indicates the distance between *ML* and footing in the *x*-direction. Two types of bamboo-filled barriers were used in the present investigation. In the first type, bamboo was placed at a center-to-center spacing of 0.5 m ($BB_{0.5}$) [Figure 5], whereas in the second type, bamboo was placed at a center-to-center spacing of 1.0 m ($BB_{1.0}$) [Figure 5]. Figures 4 and 7 show the dimensions of the wave barriers used for the current investigation.

It is important to consider the durability characteristics of bamboo before using it on-site, where it is exposed to the atmosphere. Bamboo is vulnerable to attacks by fungi and insects. Therefore, bamboo should be adequately treated to prevent degradation. To enhance the serviceability of bamboo, it was subjected to a three-month seasoning process in the current investigation.

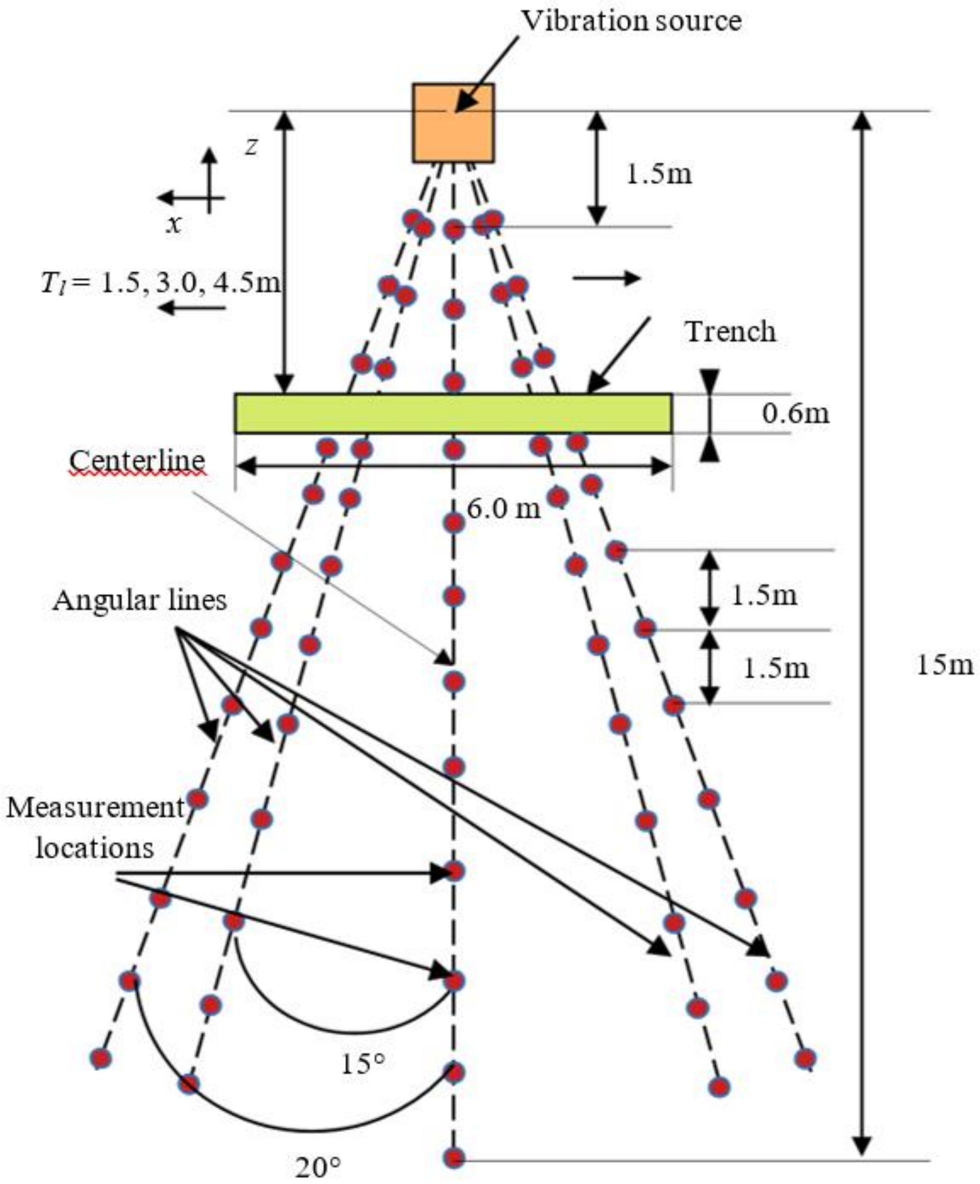


Fig. 4 Testing scheme for evaluating the vibration mitigation behavior of different barriers

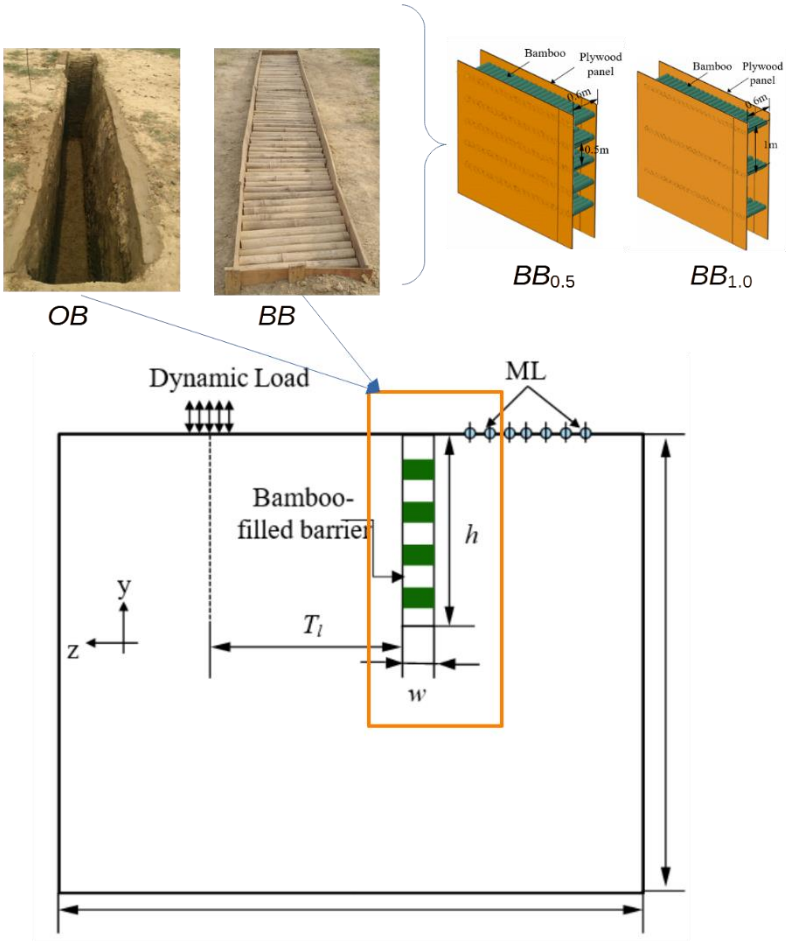
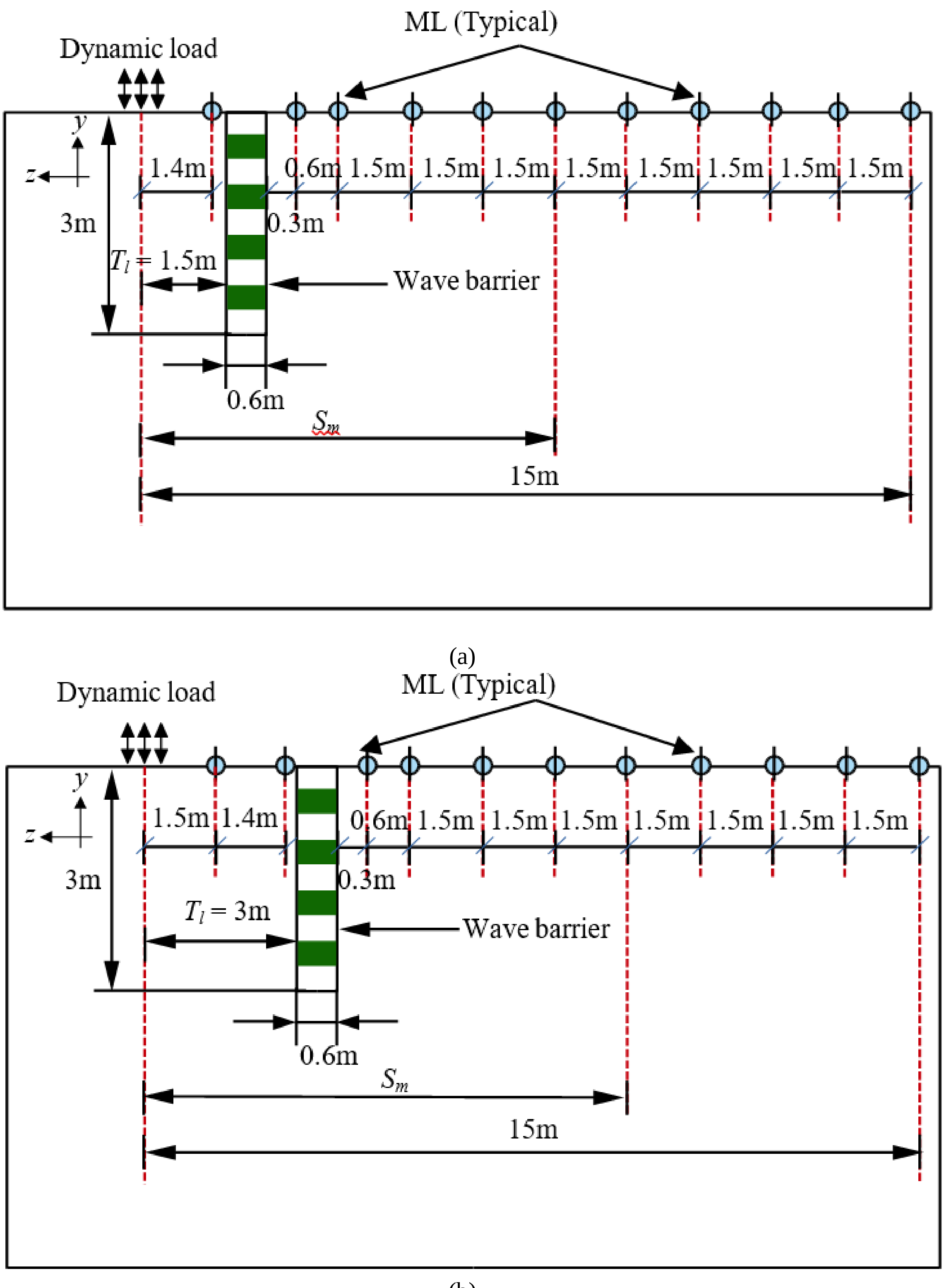


Fig. 5 Different trenches used for the experiments

Fig. 6 Installation of BB at the site

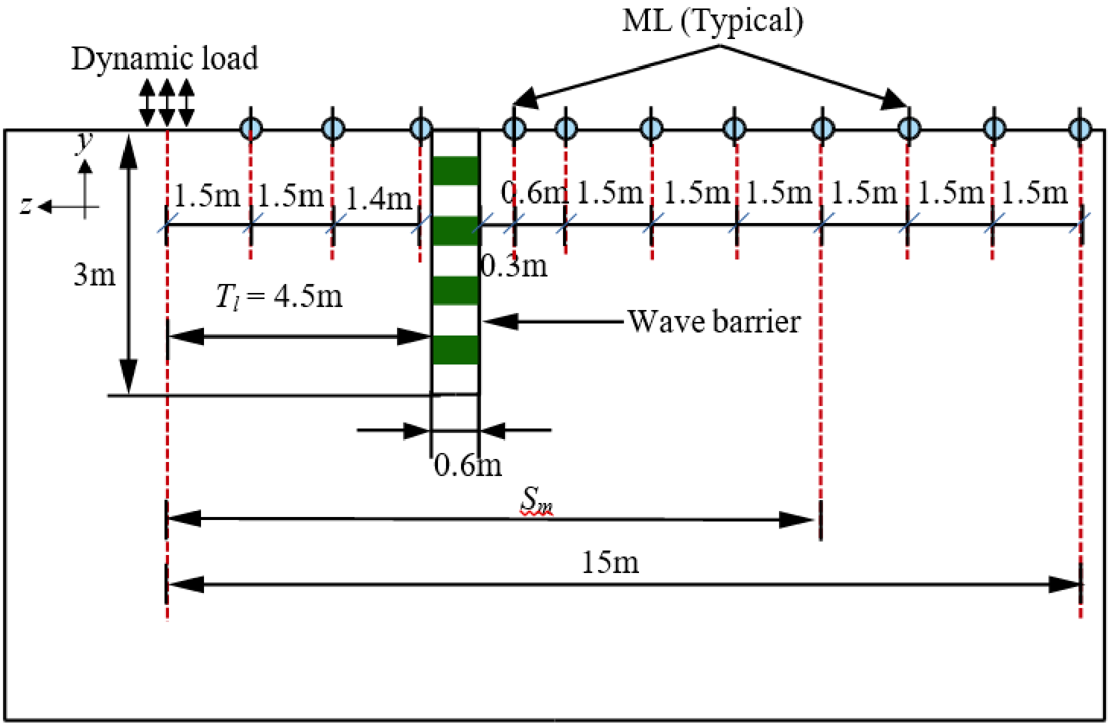


ML (Typical)
Dynamic load
y
z
1.4m
0.6m
1.5m
1.5m
1.5m
1.5m
1.5m
1.5m
1.5m
1.5m
3m
0.3m
T_l = 1.5m
Wave barrier
0.6m
S_m
15m

(a)

ML (Typical)
Dynamic load
y
z
1.5m
1.4m
0.6m
1.5m
1.5m
1.5m
1.5m
1.5m
1.5m
1.5m
3m
0.3m
T_l = 3m
Wave barrier
0.6m
S_m
15m

(b)



(c)

Fig. 7 Schematic representation of the testing program for investigating the influence of trench location: (a) T_l = 1.5 m, (b) T_l = 3.0 m, and (c) T_l = 4.5 m

RESULTS AND DISCUSSION

1. Vibration Mitigation Behavior

As mentioned earlier, the vibration mitigation behavior of *BB* and *OB* was assessed through the analysis of measured responses across different *ML*s (Figures 4 and 7). The responses are presented using normalized vertical displacement (U_{ny}) to provide insight into the vibration attenuation characteristics of different wave barriers. To calculate the U_{ny} values, the peak-particle displacement (*PPD*) at different *ML*s was normalized using the *PPD* at the first *ML*. Figures 8 – 10 show the variation of U_{ny} with S_m for f_i ranging from 1500 rpm to 2700 rpm and for different T_l.

It can be observed from Figure 8 that at f_i = 2700 rpm, S_m = 15.0 m, and T_l = 1.5 m, the U_{ny} values for *WB*, *OB*, $BB_{1.0}$, and $BB_{0.5}$ are 0.14, 0.01, 0.04, and 0.03, respectively. This indicates that the reduction in vibrations is greater for *OB* compared to *BB*, with the U_{ny} value for *OB* being 75% lower than $BB_{1.0}$ and 66.7% lower than $BB_{0.5}$. Thus, it can be concluded that at the farthest measurement location (S_m = 15.0 m), *OB* is the most effective barrier in reducing vibrations. The U_{ny} values at different *ML*s decrease with an increase in f_i, which may be attributed to the damping characteristics of the soil (Gao et al., 2006; Surapreddi and Ghosh, 2022a). Furthermore, the minimum U_{ny} values beyond the barrier are observed at S_m = 15.0 m, 7.5 m, and 13.5 m for *OB*, $BB_{1.0}$, and $BB_{0.5}$, respectively. Thus, it can be inferred that wave transmission and reflection play an important role in the vibration mitigation behavior of the barriers. It can be noted from Figure 9 that for the same f_i and *ML* but for T_l = 3.0 m, the U_{ny} values for *WB*, *OB*, $BB_{1.0}$, and $BB_{0.5}$ are 0.13, 0.02, 0.05, and 0.04, respectively. Similarly, at the same f_i and *ML* but for T_l = 4.5 m, the U_{ny} values for *WB*, *OB*, $BB_{1.0}$, and $BB_{0.5}$ are 0.19, 0.04, 0.04, and 0.04, respectively (Figure 10). Thus, it can be concluded that at T_l = 1.5 m and S_m = 15.0 m, *OB* outperforms *BB*. In contrast, as T_l increases the performance of the barriers is comparable. Therefore, the trench location plays an important role in the vibration mitigation behavior. It can be observed that the U_{ny} values for *OB* are lower compared to *BB*. Similar findings for open and in-filled barriers are reported in the literature (Alzawi and El Naggar, 2011; Saikia and Das, 2014; Majumder and Ghosh, 2016; Bose et al., 2018; Surapreddi and Ghosh 2023).

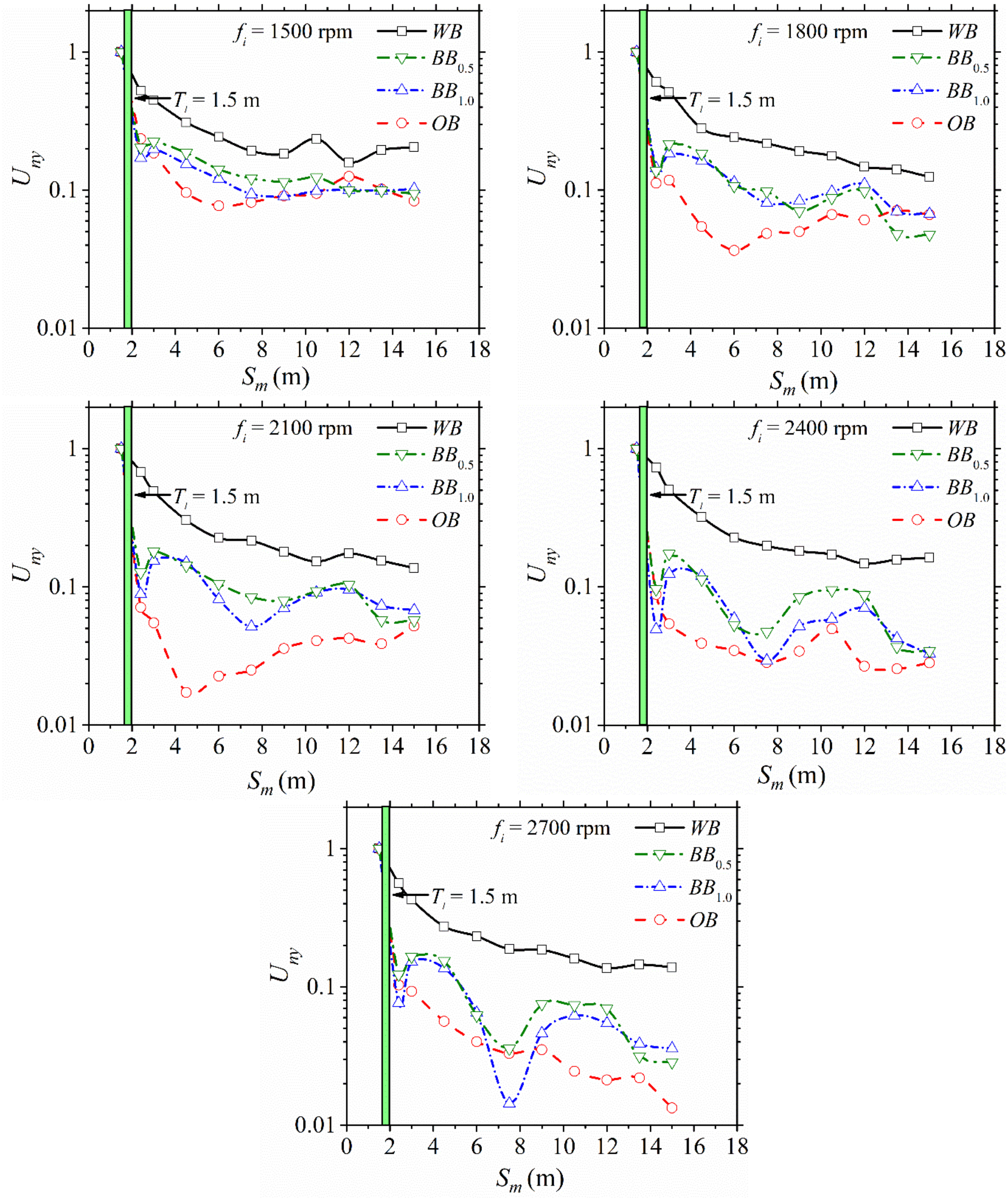


Fig. 8 Variation of U_{ny} with S_m for different frequencies at $T_l = 1.5$ m

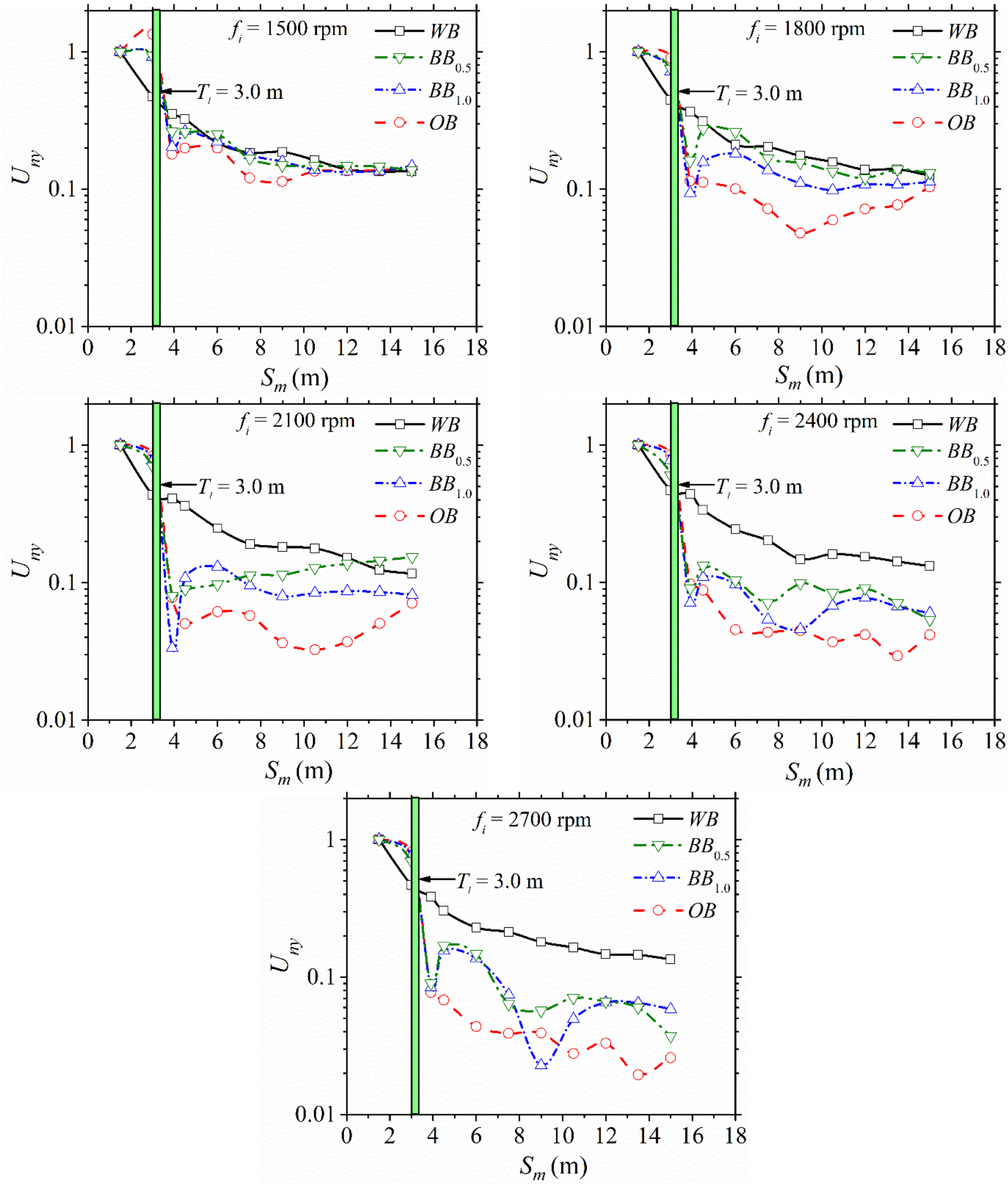


Fig. 9 Variation of U_{ny} with S_m for different frequencies at $T_l = 3.0$ m

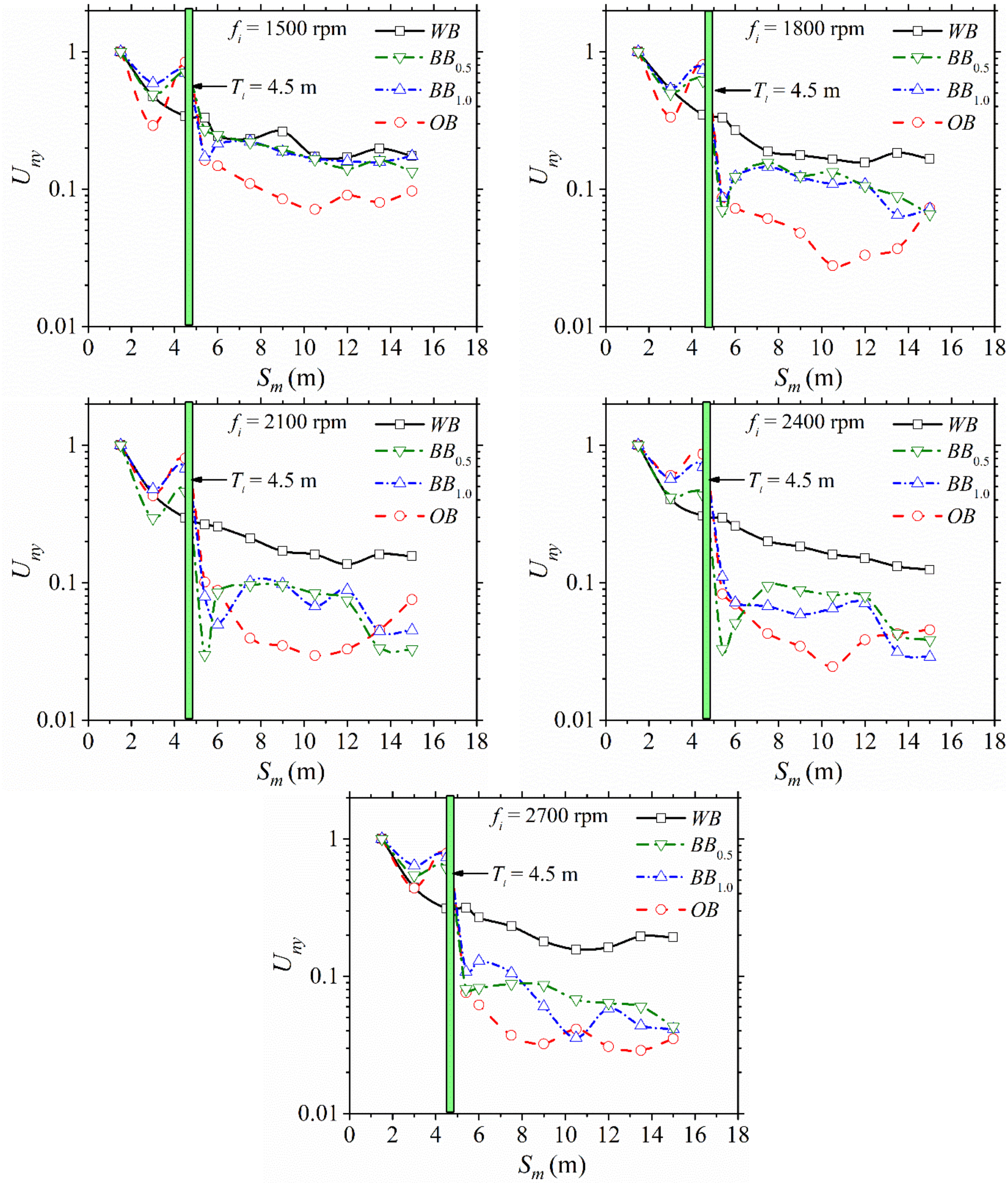


Fig. 10 Variation of U_{ny} with S_m for different frequencies at T_l = 4.5 m

2. Amplitude Reduction Coefficient Contours

The vibration mitigation behavior of different barriers can be assessed using the amplitude reduction coefficient (*ARC*). *ARC* is defined as the ratio of the peak-particle displacement (*PPD*) after barrier installation to the *PPD* before barrier installation. The *ARC* contours for *OB*, $BB_{1.0}$, and $BB_{0.5}$ are shown in Figures 11 – 13. It can be noted from Figures 11 – 13 that the performance of *OB* and *BB* improves with an increase in f_i. Additionally, the reflection before the barrier is higher for *OB* (Figure 11) compared to $BB_{1.0}$ (Figure 12) and $BB_{0.5}$ (Figure 13). The *ARC* contours also exhibit slight asymmetry, which may be attributed to the soil stratification. Furthermore, the contours indicate that *OB* is more effective in mitigating vibrations compared to both *BB* configurations, although the performance of *BB* is also satisfactory. $BB_{1.0}$ performs better than $BB_{0.5}$ due to the lower volume of filler material. Similar findings are reported in the literature (Woods, 1968; Surapreddi and Ghosh, 2023).

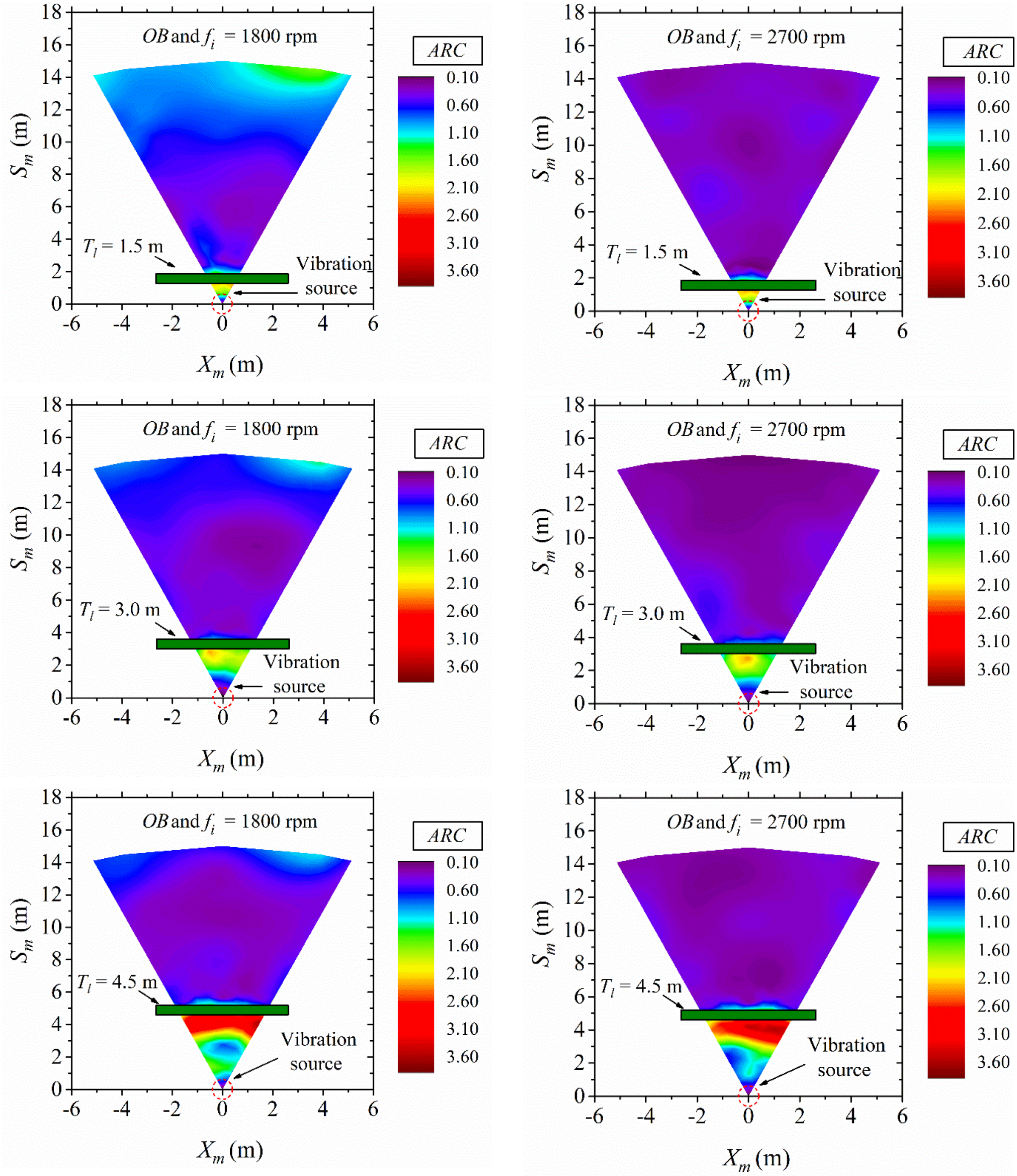


Fig. 11 *ARC* contours for *OB* at different trench locations

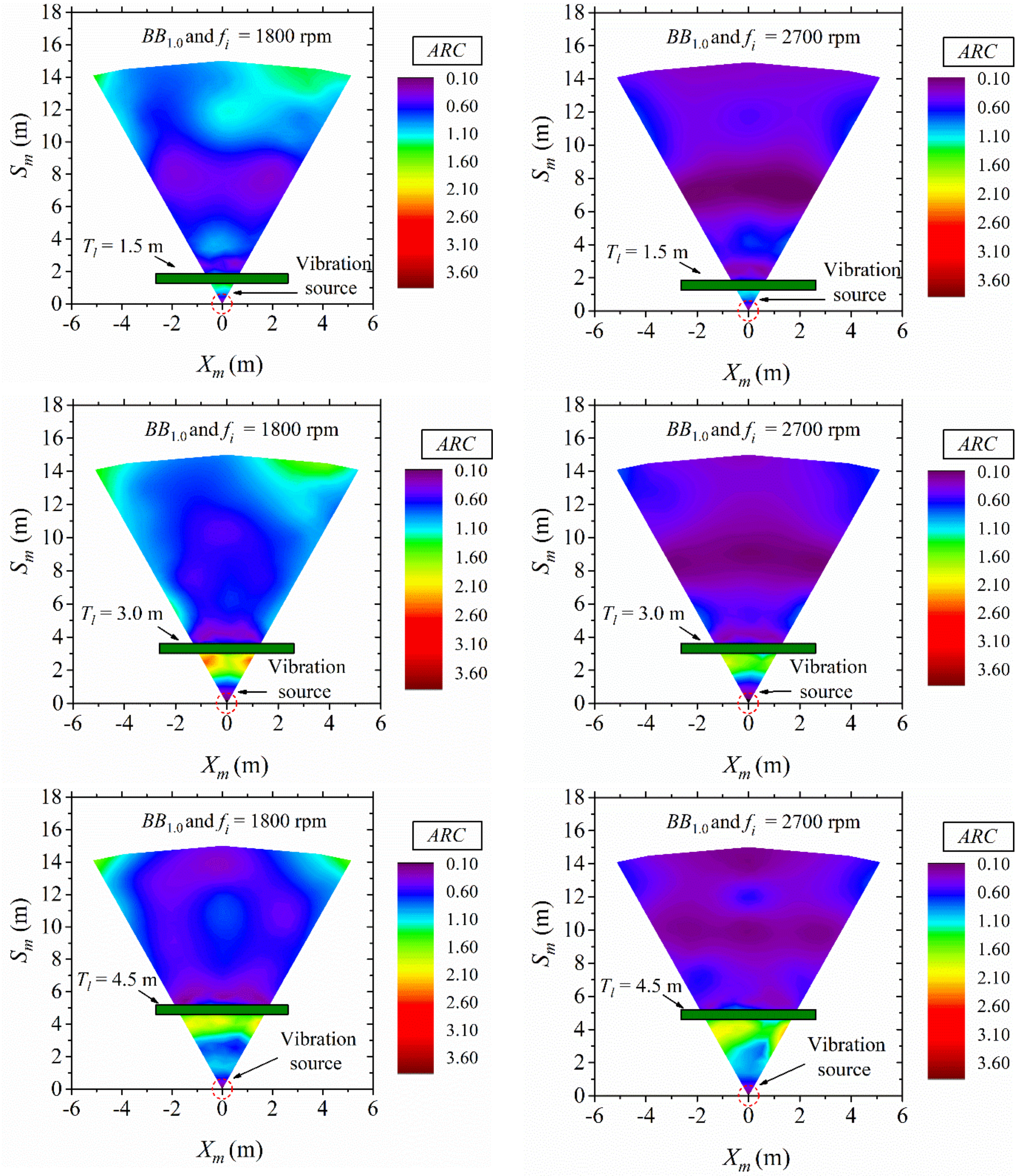


Fig. 12 *ARC* contours for $BB_{1.0}$ at different trench locations

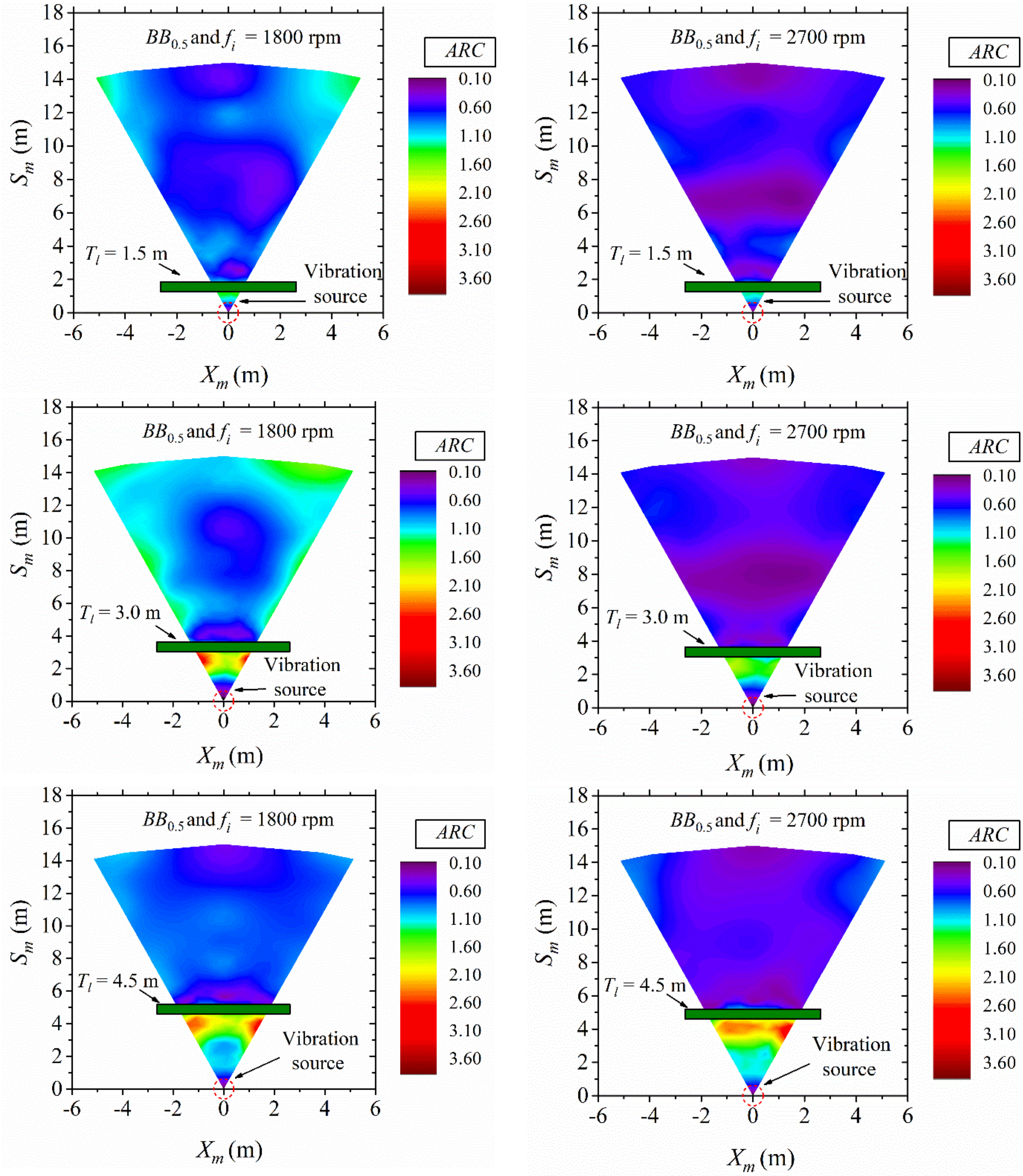


Fig. 13 *ARC* contours for $BB_{0.5}$ at different trench locations

Based on the *ARC* contours, it can be conceived that the barriers are effective in mitigating vibrations at higher frequencies. It can be noted from Figures 11 – 13 that the performance of *OB* and *BB* improves with an increase in f_i. Accordingly, *BB* could be effective in attenuating vibrations induced by fast-moving trains or metro systems, which typically generate ground-borne vibration frequencies in the range of 1500 rpm to 3600 rpm (Krylov, 1995; Madshus and Kaynia, 2000; Hung and Yang, 2001). Thus, the efficacy of *BB* in attenuating vibrations makes it an attractive alternative for in-filled wave barriers. Therefore, *BB* can be successfully implemented in the field to mitigate unwanted ground-borne vibrations.

CONCLUSIONS

The vibration mitigation behavior of *BB* and *OB* are explored using experimental investigations. The influence of trench location, measurement location orientation, and barrier configuration on the performance of *BB* and *OB* is critically explored. Practical insights into the installation process and precautions for the installation of *BB* panels are provided, offering valuable guidance for field engineers in real-world applications. The important findings can be listed as:

- At the farthest measurement locations, *OB* performs better than *BB*.
- At S_m = 15 m and T_l = 1.5 m, the U_{ny} values for *OB* are 75% lower than those for $BB_{1.0}$ and 66.7% lower than $BB_{0.5}$.
- Wave transmission and reflection play a significant role in the vibration mitigation behavior of the barriers.
- The performance of *BB* and *OB* improves with an increase in f_i.
- $BB_{1.0}$ performs better than $BB_{0.5}$ due to the lower volume of filler material.

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