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ORIGINAL PAPER

Experimental Study on Reutilization of Waste Rubber Chips with Sheetpiles as a Coupled-Wave Barrier to Reduce Ground-Borne Vibrations

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Abstract

Purpose Environmental and man-made vibrations due to various sources have become an environmental issue in recent years. Wave barriers such as open and in-filled trenches have been commonly used in the mitigation of these vibrations. Even though the open trench has exhibited better performance than the others, it may not be applicable or feasible in many cases. Therefore, soft and stiff barriers have been used for the same purpose. The present study aims to reveal the vibration isolation performance of not only single barriers such as rubber chips in-filled trenches and sheetpiles but also a novel barrier, rubber chips-sheetpile coupled barriers.

Methods Rubber chips and sheetpiles were employed as soft and stiff wave barriers, respectively. The screening effectiveness of rubber chips, sheetpiles and their coupled form was examined through comprehensive field tests. Vibrations having frequencies in the range of 10–80 Hz were generated by a state-of-the-art mobile seismic shaker and measured by highly sensitive acceleration and velocity pickups in the absence and presence of these wave barriers. The effectiveness of the wave barriers was quantitatively determined.

Results and conclusion While the sheetpile was more effective than rubber chips at low frequencies, the case was vice versa at higher frequencies. However, the coupled wave barrier outperformed other barriers in each case. If one barrier could not provide the required amount of isolation or is only effective within a limited range of frequency, using a coupled barrier with the installation of the other may significantly provide better vibration isolation.

Keywords Environmental vibrations · Vibration isolation · Waste material · Coupling effect · Field experiment

Introduction

Vehicular [1] and railway [2, 3] traffic, subway [4], machinery operations [5], construction works [6–8], blasting [9] or impact [10] may produce undesirable vibrations. The ground-borne vibrations due to these various sources cause disturbance not only to humans living in the immediate vicinity [7, 11] but also to sensitive cultural structures [12]. In addition, it has become a problematic issue for structures built on these vibration sources due to land utilization problems in over-populated countries [13]. Connolly et al. [14] compiled commercial reports, on more than 1500 railway track sections, regarding vibration and noise in 9 countries and revealed that 49% of the cases required a proper mitigation measure due to exceedance of tolerable limits. Approximately 20% of Europeans suffer from vibration and noise [15, 16]. In brief, the isolation of ground-borne vibrations has become an uncontrovertible environmental issue. While improvements in the quality of the track and reduction of local defects can contribute to mitigating railway-induced vibrations [2], employment of expanded-polystyrene blocks [3], special base isolators [4] or geosynthetics encapsulated sand-rubber mixture [17] may be proper mitigation methods

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depending on the vibration source. In cases where the direct isolation of the source may not be applicable or feasible, wave barriers have been commonly used. Creating a discontinuity/obstacle in the direction of the movement, propagation of the vibrations can be interrupted.

The first attempt to mitigate ground vibrations by wave barriers was given by Barkan [18]. The author conducted field vibration tests within a limited frequency (f) range of 11.17 Hz to 17.17 Hz. While increasing the depth and the frequency contributed to a reduction in the amplitude, increasing the length did not have a significant effect. Woods [19] conducted a series of field experiments using open trenches. He concluded that the barrier depth to Rayleigh wavelength (λ_R) should be at least 0.6 and the increase in the width did not have a significant effect. Later, many experimental [20–25] and numerical [10, 16, 26–30] studies focused on the isolation performance of open trenches. In summary, parameters affecting the screening effectiveness were the frequency of the vibrations, Rayleigh wave velocity of the medium, layering of the soil and barrier dimensions. To take into account all these parameters, the barrier dimension was normalized with the Rayleigh wavelength, a function of frequency and wave velocity. Increasing the normalized depth of an open trench mostly provided better isolation performance and the effect of the width was not remarkable.

Even though deep open trenches exhibited promising isolation performances, instability and maintenance problems have directed researchers to other types of barriers. In order to construct deep wave barriers, stiff barriers such as sheetpile [18, 19, 31–33], piles [34–39] and concrete barriers [16, 20, 40] or wave impeding blocks [41, 42] were employed. It was stated that sheetpiles could not mitigate vibrations as effectively as open trenches [18, 19]. The authors also remarked that isolation performance was mainly governed by the dimension, especially the depth. Dijckmans et al. [31] investigated the screening effectiveness of sheetpiles against railway-induced vibrations. Sheetpiles having varying depths of 12 m to 18 m were installed in parallel with a railway track. The authors concluded that sheetpiles were only effective when they were sufficiently deep compared to Rayleigh wavelength and it was proposed to employ them in soft soil conditions. However, the effectiveness was only determined in case the vibration source was a passage of a train. A frequency-based, comprehensive in-situ test was carried out by Toygar et al. [32]. The sheetpile barrier managed to reduce the amplitudes of vibrations by 44–79% within a frequency range of 30 Hz to 80 Hz and proved to be relatively effective. However, the best vibration isolation performance among these barriers was again provided by the open trench.

Another prospect to overcome the instability problem of the open trench was to fill the trench. Expanded polystyrene [6, 22, 25, 43, 44], bentonite [20, 33, 40], water [20, 22] and rubber chips [10, 40] can be exemplified as in-fill materials used in trenches. All these materials except rubber chips are either manufactured by a process or mined and processed. Rubber chips are waste materials obtained from end-of-life tires for alternative applications. Zedler et al. [45] summarized the usage area of end-of-life tires as recycling (52%), energy (40%), unknown/stock (5%) and civil engineering applications (3%) based on statistical data from 32 countries in Europe. Luo et al. [46] indicated that approximately 1.5 billion tires expire each year and become waste which can potentially pollute the environment due to their abundance. Therefore, it is important to create a new field of use for waste material. Rubber chips have a high energy absorption capacity which makes them feasible for seismic/vibration isolation purposes [47, 48]. Zeng et al. [49] employed rubber to create a high axial-low shear strength product to reduce vibrations on buildings. In most of the previous studies [10, 23, 50], the rubber chips were mixed with sand and the vibration isolation performance of the sand-rubber mixture (SRM) as a wave barrier was investigated. The SRM wave barrier proved to be effective in reducing ground-borne vibrations. It was also concluded that increasing the amount of rubber resulted in better screening effectiveness. On the contrary, Zoccali et al. [40] performed finite element analyses by employing a rubber chips-filled trench and reported vibration isolation of less than 10%. There is a gap in the literature, especially in experimental studies, regarding wave barriers filled with rubber chips only.

The screening effectiveness of a single barrier is limited in parallel with its properties. There are only limited ways, such as increasing the depth or changing in-fill material, to enhance the effectiveness. In order to achieve more isolation, the number of wave barriers can be increased by using dual trenches [25, 43] or multiple barriers [10, 34, 38, 39, 51]. In addition, some composite metamaterials, made of numerous materials, can be used to obtain more reduction than a single material can provide [52–54]. Huang et al. [53] and Ramaswamy et al. [54] used a periodic barrier consisting of polyurethane between reinforced concrete layers while Li et al. [52] employed rubber and concrete to have a periodic barrier. Similar to such composite periodic barriers, it is logical to use two different wave barriers together as a couple, thus, more reduction can be obtained. First, Barkan [18] employed a barrier consisting of a 2.8 m deep timber sheetpile located below a 1.8 m deep open trench. The 4.6 m deep coupled wave barrier presented the same isolation performance as the 4 m deep open trench did. However, it was also stated that the coupled wave barrier was not efficient in practical use. In a case study by the author, there was a group of buildings next to a street causing vibrations due to traffic. The buildings were detached from the street by open trenches and sheetpiles, however, the barrier did not prevent the vibrations on the building. It may be attributed to the existence of a deeper retaining wall than the barrier, on the street side, which may have transmitted the vibrations. McNeill et al. [5] mitigated the vibrations caused by machinery actions in a standards laboratory by 90% within the frequency range of 6–12 Hz. Even though the frequency range was very limited, it was the first successful application for an open trench-sheetpile couple. Toygar et al. [32] examined the effectiveness of such coupled barriers through field experiments and reported a reduction of 36–93% in the amplitude of vibrations with frequencies ranging from 30 to 80 Hz. Due to the aforementioned reasons, coupled wave barriers having open trenches may not be practical in all soil conditions, thus, there may be a need for in-filled material.

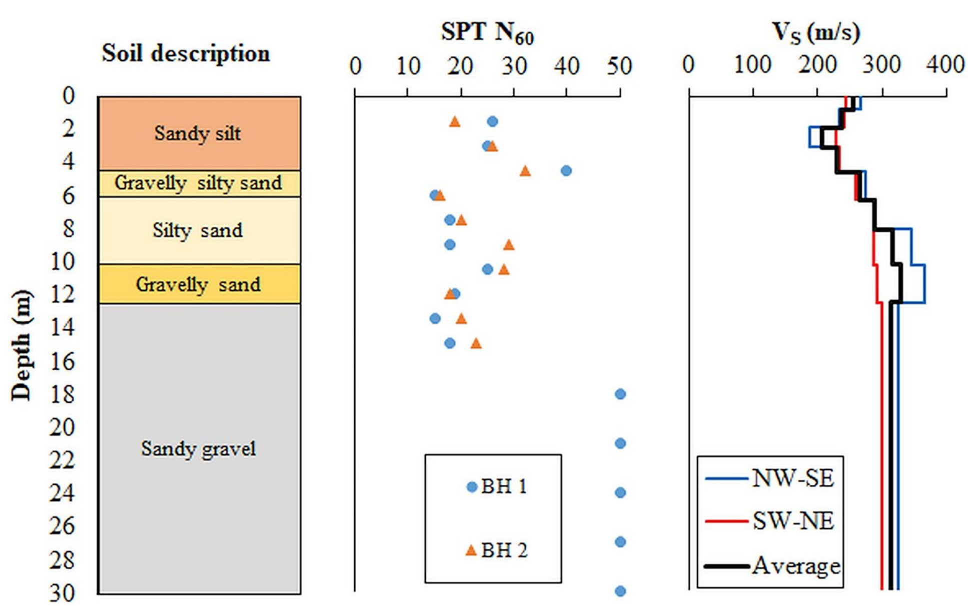
The present study aims to reveal the vibration isolation performance of sheetpile, rubber chips and rubber chips-sheetpile coupled barriers through field experiments at a wide range of frequencies in a comparative manner. In the literature, there is a lack of experimental data regarding the vibration isolation performance of sheetpiles and solely rubber-in-filled barriers. The sheetpile, whose isolation performance has only been examined in cases of either continuous vibration sources or within a limited frequency range in previous experimental studies, is selected as the stiff barrier that can be easily installed to great depths by its nature. Not only a good isolator due to its high energy absorption capacity but also being a waste material enabled rubber chips to be used as the soft barrier in this study. In this way, an environmental issue, which is disturbance due to ground-borne vibrations, is addressed within an environmental aspect such as the reutilization of waste rubber chips. As a novelty in this study, sheetpile, due to its depth, and rubber chips, due to their high energy absorption capability, are employed together to form a coupled barrier that can provide more vibration isolation than single ones can.

Properties of the local soil

The full-scale field vibration tests were carried out in an unemployed, flat area in Mentese (Mugla, Turkey) due to its feasible conditions. It was quite distant from traffic and human activities which may cause additional vibrations during the tests. Prior to the vibration tests, a detailed soil survey was performed to discover local site conditions. Two boreholes (BH) were drilled to the depth of 30 m and 15 m, respectively. Standard penetration test (SPT) was conducted along the boreholes at every 1.5 m depth till the first 15 m, afterwards, the test was repeated with a depth interval of 3 m. At each test, SPT N_{60} blow numbers (Fig. 1) were recorded and undisturbed soil samples were collected. The top 10.5 m was mostly a mixture of sand and silt with an increasing amount of sand with increasing depth. Dissimilarly, a very stiff soil band with a thickness of 1.5 m, gravelly silty sand, was encountered around the depth of 5 m. There was a gravelly sand layer at the depths of 10.5 m and 12 m, resting on sandy gravel. No groundwater table was observed. The soil profile is shown in Fig. 1.

Following the identification of the physical properties of the local soil, two Multichannel Analysis of Surface Waves (MASW) tests were carried out to obtain the dynamic properties of the surrounding soil. In the first test, geophones were deployed along a 100 m long measurement line with a spacing of 4 m in the NW–SE direction. A series of impacts were generated by a sledgehammer. Knowing the location of the geophones and measuring the arrival time of impulses, the shear wave velocity (V_S) profile of the soil was obtained

Fig. 1 Properties of the local soil



in this direction. The test was repeated in the SW-NE direction crossing the first measurement line. The variation of the average shear wave velocity with the depth was obtained by using both measurements and presented in Fig. 1. The average V_S at the surface was 255.5 m/s and ranged between 208 m/s and 329 m/s. The average P-wave velocity (V_P) at the surface was 431.5 m/s. By using Eq. (1), Poisson's ratio (ν) was calculated as 0.23 [55].

$$\frac{V_S}{V_P} = \sqrt{\frac{1-2\nu}{2(1-\nu)}} \quad (1)$$

Knowing shear wave velocity and Poisson's ratio, the Rayleigh wave velocity (V_R) was obtained as 233 m/s by using Eq. (2) [55]:

$$V_R = \frac{0.86 + 1.14\nu}{1+\nu} V_S \quad (2)$$

Test setup

The isolation performance of a barrier depends on many parameters such as type of vibration source [53], excitation frequency [22–24, 32, 53], source-barrier distance [20–22], local soil conditions [22, 24], barrier dimension [18] etc. The types of sources can be grouped into two categories: moving and stationary vibration sources. Trams [2] and high-speed trains [40] are typical examples of moving sources, while machinery actions [5], construction operations [6] or blasting [9] are deemed stationary ones. The present paper focused on ground-borne vibrations due to stationary vibration sources. Another influential parameter on the effectiveness of a wave barrier is the excitation frequency. Kowalska-Koczwara and Stypula [56] compared different standards (national standards of Poland, the UK and Germany and the international standard ISO) regarding human exposure to vibrations. The one thing in common for all standards is the frequency (f) range, being between 1 and 80 Hz. In order to determine the effectiveness of wave barriers in a frequency-oriented aspect, it was aimed at generating continuous vibrations that covered this frequency range. Many experimental studies [19–21, 25] employed mechanical or electrical oscillators to create vibrations in the field. The oscillator was fixed on a small concrete or steel foundation. In more recent studies [22, 57], asphalt and soil vibratory plate compactors were used to generate vibrations due to their easy mobilization. However, the frequency range was limited and the adjustment of excitation frequency was not sensitive. In the most recent experimental studies [32, 53, 54], state-of-the-art shaker trucks, mostly employed for seismic field studies, were used as a vibration source. Their easy mobilization in the field and adjustment of wide-range frequencies with high precision enable them feasible as a vibration source in field tests. In the present study, the same mobile seismic shaker used by Toygar et al. [32] was employed. The properties of the shaker were described in detail in that study. The shaker truck created vibrations on the surface by means of a vibrating plate attached to itself (Fig. 2). At each test, it generated vibrations for a duration of 15 s with an average centrifugal force of 10 kN. The excitation frequency was increased from 10 to 80 Hz by 10 Hz at each test.

Baziar et al. [43] defined vibrations as fluctuational motions, which can be expressed by displacement, velocity and acceleration, about a neutral axis. Additionally, Alzawi and El Naggar [21] stated that the effectiveness of a wave barrier can be assessed by observation of displacement, velocity and acceleration. Accordingly, the amplitude of vibrations can be measured by one of these three indicators. Toygar et al. [32] investigated the usage of different sensors to measure the magnitude of vibrations in previous experimental studies and concluded that either accelerometers or velocity pickups/geophones were utilized to measure the amplitude of vibrations in most of the studies. As a novelty, both accelerometers and geophones were simultaneously used to obtain the amplitudes of vibrations by Toygar et al. [32]. In the present study, the same measurement system was used. Accelerometers and geophones, deployed next to each other, were used to measure the amplitudes of vibrations in a line as shown in Fig. 2. Acceleration sensors are Sensebox 7001 uniaxial accelerometers which can operate within the range of -2 g to + 2 g with a precision of 10^{-5} g. 8 accelerometers were buried 7.5 cm below the surface at specific locations to satisfy full contact with the soil. Immediately next to accelerometers, 8 geophones were deployed and fixed into the ground by means of their spikes. The geophones could only detect vibrations at frequencies higher than 4.5 Hz due to their inner high-pass filter. Since the minimum excitation frequency was 10 Hz, the geophones can measure the amplitudes of vibrations accurately for this test configuration. Nevertheless, accelerometers were deemed as the first option to monitor the vibrations due to their wide-range of operation frequency, the geophones were

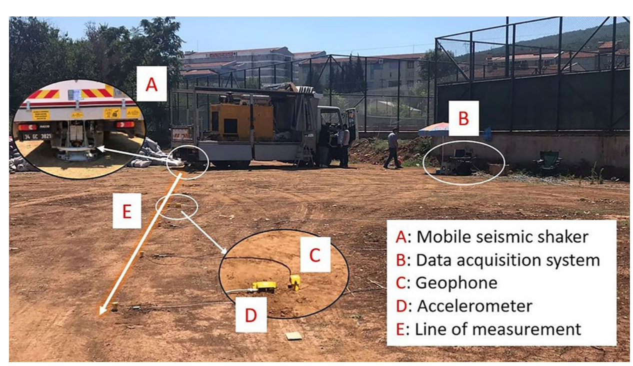


Fig. 2 Vibration source and field measurement system

to be used as a backup measuring method. Accelerometers and geophones were connected to a 24 bit dynamic data logger having 16 channels. Thus, simultaneous measurements were performed by both types of sensors. The amplitudes of vibration measured by the sensors were recorded by the Testbox 2010 data logger with a sampling rate of 2 kHz and stored on a computer during the tests.

The present study aimed to investigate the effectiveness of different wave barriers within a wide range of frequencies. In accordance with this purpose, accelerometers and geophones were deployed at the specific locations shown in Fig. 3. The mobile seismic shaker generated vibrations from 10 to 80 Hz. In the absence of any wave barrier (free-field condition), the amplitudes of vibrations were measured and recorded.

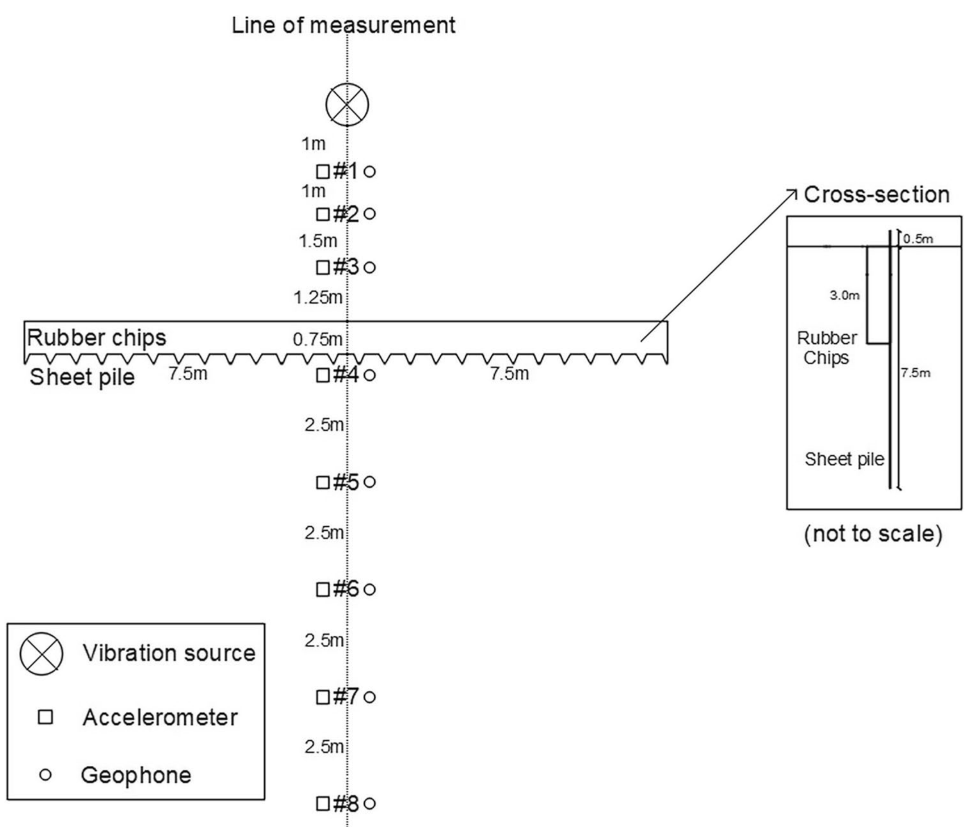
Wave barriers

The idea of vibration isolation by wave barriers is based upon the reduction of incoming wave amplitude by creating a discontinuity in the direction of movement. Open trenches create gaps on the surface so that waves can not propagate on the surface and must move along the subsurface, then, direct to the surface. Other types of barriers provide amplitude reduction by either damping the motion or reflecting/diffracting. While soft barriers offer high damping, stiff barriers can be installed to great depths, then, deeper barriers can be obtained. It was aimed at utilizing the advantages of both soft (rubber chips) and stiff (sheetpile) barriers together in the coupled form of the wave barrier.

Prior to the installation of wave barriers, the field vibration tests as described in Fig. 3 were conducted in the absence of any wave barrier. These tests were called benchmark tests in which the attenuation of vibrations could be observed in free-field conditions. Then, 8 m deep, 60 cm wide sheetpiles with a thickness of 1 cm were installed into the ground side by side to constitute a 15 m long sheetpile barrier (Fig. 4a). The same U-shaped steel sheetpiles as used by Toygar et al. [32] were employed. The sheetpile was not installed as a support or bracing element, hence, its dimension was selected due to its abundant commercial availability in Turkey. For easy extraction, approximately 50 cm of the sheetpiles were undriven, thereby, a 7.5 m deep sheetpile wave barrier was obtained in the field. The field vibration tests were repeated in the presence of this wave barrier.

The waste rubber chips were procured by a process that steel beltings in end-of-life tires were removed and then crushed into pieces [47]. The rubber chips employed in the present study were grated from a 22 mm grater and had a density of 400 kg/m^3. A 3 m deep, 75 cm wide trench was excavated alongside the sheetpiles. The width was practically determined due to the fact that the bucket of the excavator was 75 cm. The trench was filled with waste rubber

Fig. 3 Locations of wave barriers and measurement system



a)

b)

c)

Fig. 4 Wave barriers **a** sheetpile **b** rubber chips-sheetpile coupled barrier **c** rubber chips

chips. In this way, a sheetpile-rubber chips wave barrier was obtained in the field (Fig. 4b). The field vibration tests were conducted in the existence of the coupled wave barrier. At last, the sheetpiles were extracted from the soil, then, the same field vibration tests were repeated in the case of the rubber chips wave barrier (Fig. 4c). Properties

Table 1 Properties of wave barriers and testing

	Sheetpile	Rubber chips
Density (kg/m^3)	7850	400
Particle size (mm)	–	< 22
Depth (m)	7.5	3
Length (m)	15	15
Thickness/Width (m)	0.01	0.75
Source-barrier distance (m)	5.5	4.75
Excitation frequency (Hz)	10, 20, 30, 40, 50, 60, 70, 80	
Duration (s)	15	
Sampling rate (Hz)	2000	

of the wave barriers along with the test parameters are summarized in Table 1.

Results and discussion

Test data

The field vibration tests were performed for free-field conditions and three wave barriers within a wide range of frequencies. To easily address the relevant test, the tests were named in the following order: Initials of the test (NB: no barrier, RC: rubber chips, SP: sheetpile, RC-SP: rubber chips-sheetpile coupled barrier)—excitation frequency (10–80). For example, NB-30 refers to the vibration tests performed in case of no barrier at 30 Hz. Analogically, RC-SP-80 refers to the test in the existence of the coupled barrier at 80 Hz of vibrations.

Before the tests, the vibrations on the site were monitored if there were any and it was concluded that no vibrations were detected by the sensors. Then, the seismic mobile truck was turned on and it was observed that the truck and its power supply generated vibrations at the frequency of 20 Hz even though its vibrating plate was not operated. The vibrations during the tests were the ones, intentionally generated, and the ones due to the power supply of the seismic mobile shaker. Therefore, acceleration- and velocity–time histories were filtered against ambient noise by using a 4th-order Butterworth bandpass filter with a precision of ± 2 Hz [58]. For example, the upper and lower bounds of the filter were 78 Hz and 82 Hz when f = 80 Hz. However, the noise could not be filtered at the tests when f = 20 Hz since the frequencies of the intentionally generated vibrations and noise due to the truck overlapped. Therefore, all the tests conducted at 20 Hz were excluded from the assessment.

Amplitudes of vibrations were measured by both accelerometers and geophones. At the end of each test, acceleration-time and velocity–time histories were obtained by using the direct measurement record of the sensor and also by integration or derivation of the other sensor data by time. Randomly selected exemplary acceleration-time and velocity–time histories obtained by the measurement of both sensors are presented in Fig. 5 and 6, respectively. It was observed that both time histories were compatible with one another, as also reported by Toygar et al. [32].

Using the original records, peak particle acceleration (PPA) and peak particle velocity (PPV) were obtained at all measurement points (Fig. 3) for all the tests. Then, peak particle amplitudes were normalized with the one obtained at measurement point #1 in the relevant test. For example, PPA at #5 in the SP-50 test was divided by the PPA at #1 in the same test. The same procedure was also performed for the normalization of PPV values. In this way, dimensionless amplitudes were obtained at each measurement point in all tests. The variations of normalized amplitudes obtained from different types of sensors are shown in Fig. 7. The variations in random cases proved that both sensors compatibly measured the vibrations. Therefore, it is convenient to use the data measured by either type of sensor. For brevity, the rest of the study only regarded the measurements by accelerometers.

The PPA measured at point #1 ranged from 0.05 g to 0.3 g depending on the frequency. The normalized amplitude at #8 was generally less than 0.01 and even 0.001 in some cases. Accordingly, the acceleration level was 10^{-4}—10^{-5} g in some cases which was very close to the lower boundary of perception for accelerometers. Therefore, it may not be very accurate to use the data at this point and results obtained at #8 were excluded from further evaluations. Using 8 accelerometers at these layouts in the field enabled us to observe the dissipation of vibrations.

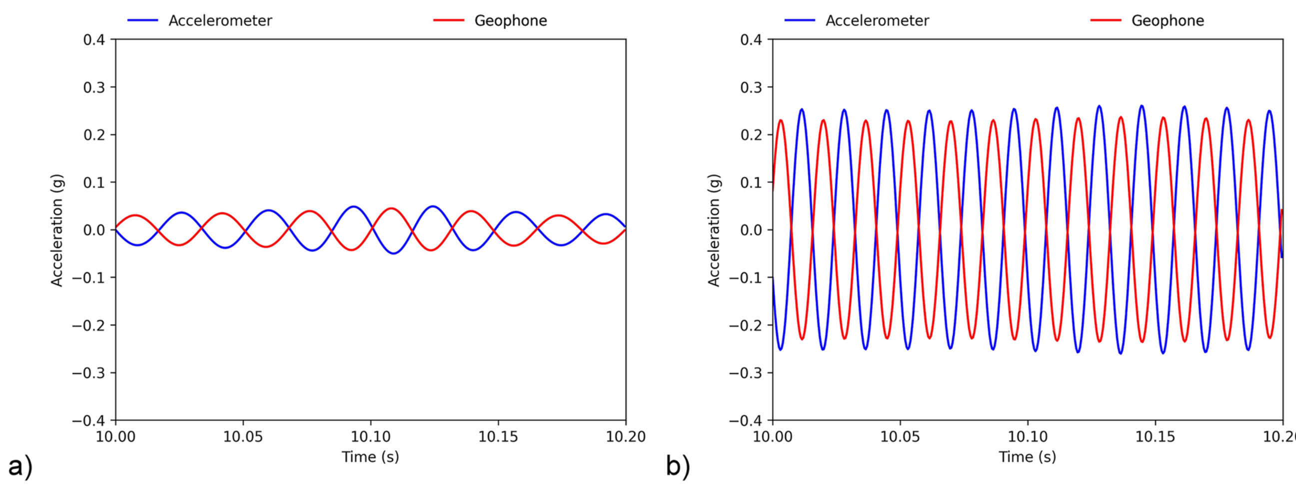


Fig. 5 Acceleration-time histories obtained at #1 for the test RC-SP. **a** f = 30 Hz **b** f = 60 Hz

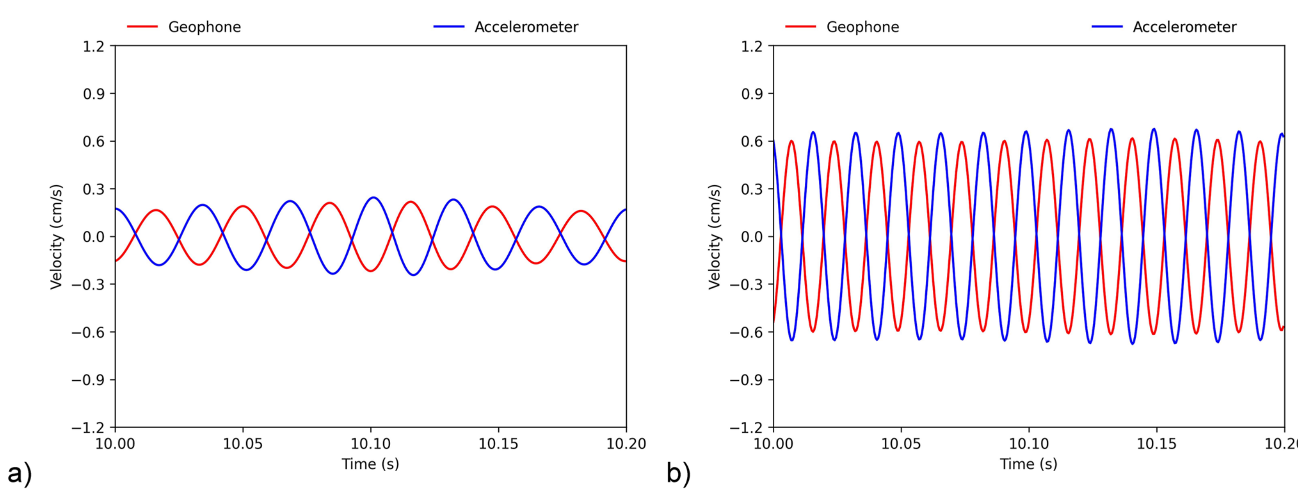


Fig. 6 Velocity–time histories obtained at #1 for the test RC-SP. **a** f = 30 Hz **b** f = 60 Hz

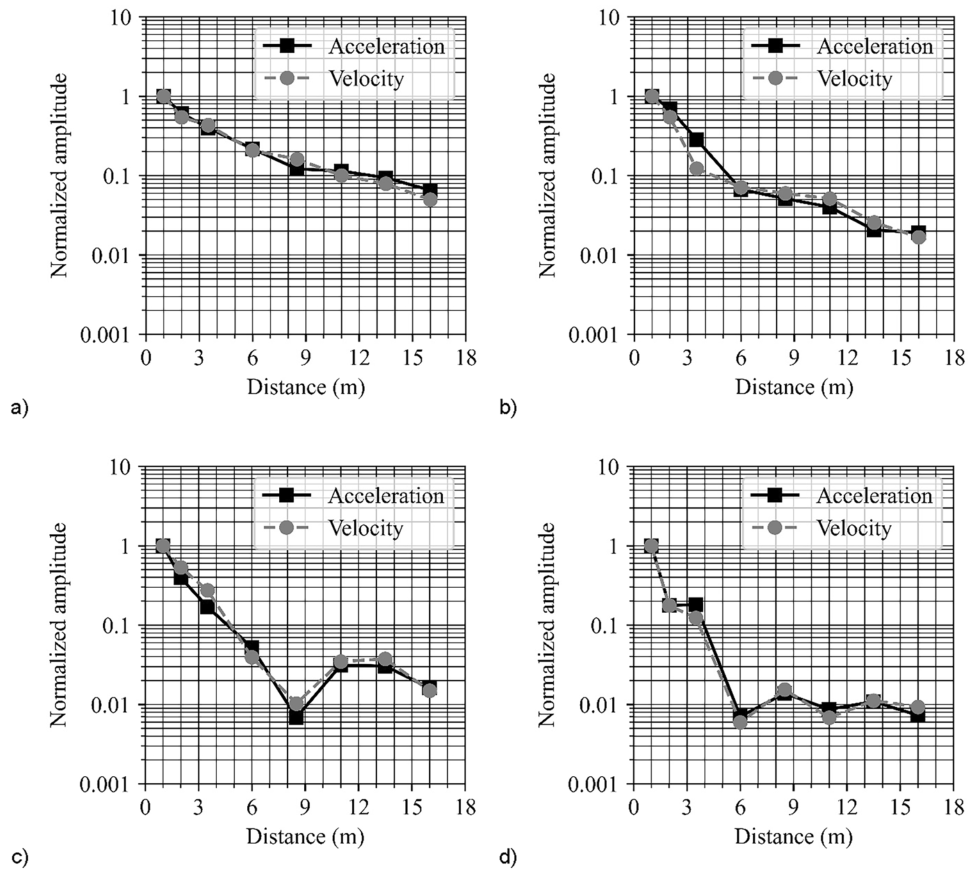


Fig. 7 Normalized amplitudes obtained by different sensors at the tests. **a** NB-30. **b** RC-40. **c** SP-50. **d** RC-SP-80

The efficiency of wave barriers

Miller and Pursey [59] examined the vibrations due to vertically oscillating sources on the surface and stated that 67% of them propagated as Rayleigh waves. Therefore, it can be deduced that the efficiency of wave barriers in the mitigation of ground-borne vibrations mainly depends on their capability of mitigating the Rayleigh waves. Due to the aforementioned reasons in the Introduction part, the dimension of the wave barriers can be normalized with the relevant Rayleigh wavelength. In this way, the effect of the local soil's Rayleigh wave velocity, excitation frequency and the dimension of the barrier can be assessed together, as in most of the previous studies. Before evaluating the overall behavior of the wave barriers, the variation of Rayleigh wavelength (λ_R) and normalized depth (D) with the frequency was presented in Table 2.

Table 2 Normalized depths of the wave barriers

f (Hz)	V_R (m/s)	λ_R (m)	$D_{sheetpile}$	$D_{rubber\ chips}$
10	233	23.30	0.32	0.13
20		11.65	0.64	0.26
30		7.77	0.97	0.39
40		5.83	1.29	0.52
50		4.66	1.61	0.64
60		3.88	1.93	0.77
70		3.33	2.25	0.90
80		2.91	2.58	1.03

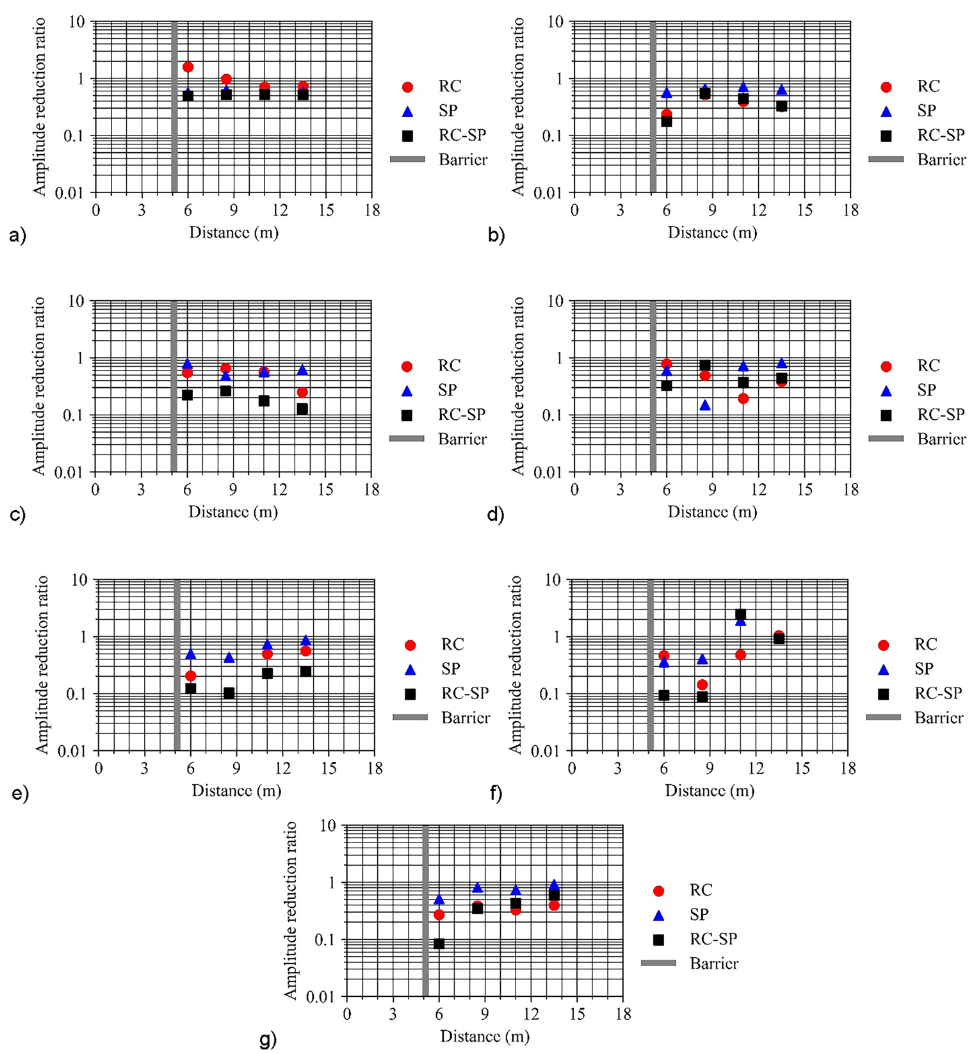
The efficiency of wave barriers can be determined by how much they reduce the vibrations when compared to the free-field conditions. The ratio of maximum dynamic amplitude in the presence of a wave barrier to the one in the free-field case is called the amplitude reduction ratio [19]. The amplitude reduction ratio (A_R) can be obtained discretely at every measurement point.

In field vibration tests, it may not be possible to generate vibrations having the exact same amplitudes in each test. Even some small fluctuations in the amplitudes at the source may result in inaccurate findings about the efficiency. Normalization of the amplitudes with the one in the first measurement point provided standard data in each test. In this way, normalized accelerations at point #1 were always 1.0 in all cases, hence, the data was comparable with other cases. The amplitude reduction ratio at each measurement point was calculated by using normalized acceleration values. It is expected to have vibration isolation in a region afterward the wave barrier. Therefore, the variation of the amplitude reduction ratio was presented only for these measurement points, namely #4, #5, #6 and #7 (Fig. 8).

Figure 8 demonstrates the variation of amplitude reduction ratio with distance at different excitation frequencies. Having an A_R bigger than 1 means no isolation, even amplification. The amplitude reduction ratios at #4 in RC-10, #7 in RC-70, #6 in SP-70 and #6 in RC-SP-70 were 1.59, 1.04, 1.92 and 2.44, respectively. The amplitudes of vibrations at these points were amplified compared with the free-field case. The occurrence of these distinct peaks was reported by many studies, especially the ones conducted in layered soils [22, 24, 27, 60]. It was stated that in- and out-phase combinations of newly generated vibrations and reflected/diffracted waves in layered soils underlain by more stiff soils may have resulted in such incidents.

The amplitude of vibration at a point is governed by the superposition of newly generated waves, partially damped waves during the passage through the body of the barrier and reflected/diffracted waves due to the wave barrier and soil layering. As the frequency of the vibrations changes, the wavelength changes as well, and different wave interferences may be observed. Considering the heterogeneity and different layering orientations of the soil, this interference may be more complex and amplitudes of vibrations at a point may fluctuate. Such fluctuations regarding amplitudes of vibrations and amplitude reduction ratios were also observed and reported by several experimental studies [19, 24] while numerical studies inherently may not exhibit such phenomena as the soil is modeled as homogenous, isotropic and horizontally layered. Woods [19] reported amplitude reduction ratio changing within several relative minima and maxima. Figure 8 shows that the amplitude reduction ratio mostly fluctuated within a range as the distance and the frequency changed. Even though rubber chips and the sheetpile presented varying performances at measurement point #4 (immediately after the barrier), the coupled barrier outperformed other barriers. It promoted the idea of using the coupled barrier. Moreover, the effectiveness of the sheetpiles decreased with increasing distance. At the last measurement point (#7), sheetpiles mostly underperformed other barrier types independent of frequency.

Fig. 8 Variation of amplitude reduction ratio with distance. **a** f = 10 Hz, **b** f = 30 Hz, **c** f = 40 Hz, **d** f = 50 Hz, **e** f = 60 Hz, **f** f = 70 Hz g) f = 80 Hz



Another important observation was that the effectiveness of the wave barriers decreased with increasing distance at higher frequencies. The tests conducted at 60 Hz and higher exhibited such an inference. When the A_R values obtained at #4 and #5 were compared with the ones at #6 and #7, the general trend showed that better isolation performance was provided in a region close to the barrier. Such was also reported by several experimental studies [23, 24].

Thus far, the screening effectiveness of wave barriers was determined discretely by using the amplitude reduction ratio. In order to assess the overall vibration isolation performance of wave barriers, the average amplitude reduction ratio ($\overline{A_R}$) was calculated by using the A_R values at #4, #5, #6 and #7 in each case. Using Eq. (3), the average barrier efficiency (BE) was determined [43]:

$$BE = \left(1 - \overline{A_R}\right) \times 100 \tag{3}$$

The average barrier efficiency was calculated for each wave barrier using a frequency-based approach. Due to the aforementioned reasons, the distinct peaks were not included in the barrier efficiency shown in Fig. 9.

The general trend showed that the sheetpiles underperformed other barriers at almost all frequencies. One exception was that the efficiency of the rubber chips, sheetpile and coupled barrier at 10 Hz was 20.17%, 43.32% and 49.11%, respectively. In this case, sheetpiles provided better isolation than rubber chips. As can be seen in Table 2, the normalized depth of the rubber chips was too shallow compared to that of the sheetpile in this case. As the frequency increased, the normalized depth of the barrier increased due to a decrease in the Rayleigh wavelength even though the barrier depth remained the same. It can be stated that the isolation of low-frequency vibrations requires a deeper wave barrier, especially at low frequencies in which the Rayleigh wavelength is high. The efficiency of the sheetpile wave barrier ranged from 25 to 43%. Even though the sheetpile did not provide a good deal of isolation in all cases, it can be considered a good alternative at low frequencies due to its depth.

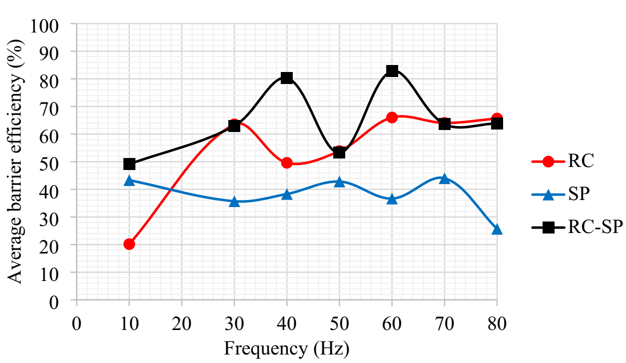


Fig. 9 Variation of the average barrier efficiency with the frequency

The efficiency of the rubber chips barrier and the coupled barrier changed in the range of 20–65% and 49–83%, respectively. Even though the barriers behaved similarly at 30 Hz, 50 Hz, 70 Hz and 80 Hz, the coupled barrier outperformed in general. Rubber chips failed to mitigate low-frequency vibrations, while the coupled barrier provided a sufficient amount of vibration isolation in all cases. For example, the efficiency of rubber chips and sheetpiles was 38.3% and 49.6% at 30 Hz, respectively. If either of the barriers was already installed in the field, coupling them as one barrier can increase efficiency by up to 80.3%. It is the case at 60 Hz, as well. While single-wave barriers performed relatively low screening effectiveness depending on the frequency, the coupled wave barrier outperformed in all cases. Therefore, the employment of the coupled barrier is also recommended in the existence of a single barrier, when the required amount of isolation is not satisfied or to have protection against vibrations at a wide range of frequencies.

Comparison with the previous experimental studies

The results obtained in the current study were compared with those reported in previous experimental studies concerning similar wave barriers within conformable limitations. There are only a limited number of studies regarding the vibration isolation performance of sheetpiles, especially the frequency-based approach. Barkan [18] employed approximately 5 m deep timber sheetpiles with a cross-section of 20 cm by 20 cm and recorded vertical amplitudes of vibrations within 10 Hz to 35.83 Hz before and after the sheetpiles. The amplitude reduction ratios were reported in a varying range of 0.44 to 0.16. It must be noted that these reduction ratios were obtained only immediately after the sheetpiling. In the current study, the amplitude reduction ratio at measurement point #4 (immediately after the sheetpile) was about 0.56 in the same frequency range as Barkan [18]. Similarly, Dijckmans et al. [31] reported the most vibration reduction as 50% around the sheetpile during the passage of a train.

As aforementioned in the Introduction part, rubber chips have mostly been mixed with sand and employed as a sand-rubber mixture (SRM) wave barrier in previous experimental studies. Chew and Leong [23] used a 1.1 m long, 0.25 m wide open trench located 1.5 m away from the vibration source and filled it with varying amounts of rubber chips. The amount of rubber chips in SRM varied between 30% (R30) to 70% (R70) by volume. The vibration isolation performance of the barrier was examined in the frequency range of 20–100 Hz. Mahdavisefat et al. [50] conducted a parametric experimental study by changing the volume of rubber chips by 10–30% within 10–600 Hz. The location of the 0.6 m wide, 3 m deep trench varied from 2.5 m to 10 m away from the source. R30 case, when the source-barrier distance was 5 m, was used in comparison as it was the

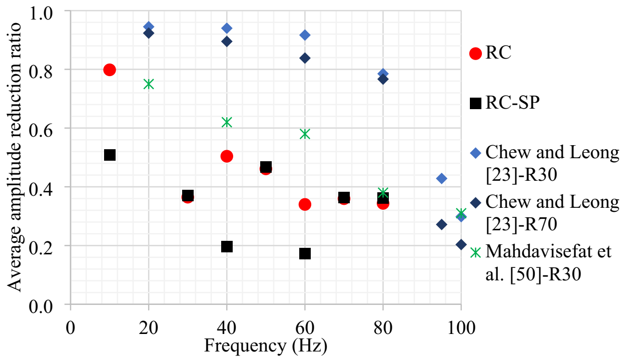


Fig. 10 Comparison of the amplitude reduction ratios reported in the present study and previous experimental studies for rubber chip wave barriers

most similar case to the current study. The findings were only evaluated for the 10–100 Hz frequency range. Since the RC-SP coupled barrier has a rubber chip component, it was also included for comparison. The average amplitude reduction ratios obtained in the present study and the previous experimental studies were compared as shown in Fig. 10.

According to Chew and Leong [23], increasing the amount of rubber chips from 30 to 70% resulted in a lower amplitude reduction ratio, meaning better isolation, as expected. Nonetheless, Mahdavisefat et al. [50] reported quite better isolation performance even in the case of 30% rubber. It can be attributed to the shallow depth of the barrier in the study [23]. The depth of the barriers in the present study and Mahdavisefat et al. [50] was the same as 3 m. Better isolation was reported in the present study as compared with [50]. Since the present study employed solely rubber chips in the barrier, increasing the amount of rubber chips from 30 to 100% may have yielded such a performance. It is also obvious that the coupled barrier outperforms at almost all excitation frequencies. To conform with the limitations of the present study, the results obtained in the previous studies were submitted up to 100 Hz. However, Mahdavisefat et al. [50] presented amplitude reduction ratios up to 400 Hz and reported varying A_R values in the range of approximately 0.25 to 0.35. Beyond 100 Hz, these values fluctuated within this range and increasing frequency did not offer any more substantial reduction. Such an observation and fluctuation were also seen in the current study, as well.

Conclusion

The study focused on the utilization of sheetpiles, waste rubber chips and the rubber chips-sheetpile coupled wave barrier for the mitigation of ground-borne vibrations. The efficiency of the wave barriers was quantitatively determined through comprehensive field vibration tests within a wide range of frequencies. The main conclusions are summarized below:

In general, rubber chips exhibited better performance than the sheetpile. However, isolation of low-frequency vibrations requires deeper barriers such as sheetpiles. It may be better to use sheetpiles at low frequencies and rubber chips at higher frequencies.

The coupled barriers provided the best performance, independent of the frequency. If one barrier is not sufficient or only effective within a limited range of frequency, using a coupled barrier by the installation of the other may significantly provide better vibration isolation.

The field tests were conducted on layered soil having stiffer soil at the bottom. Therefore, some distinct peaks were observed in some of the test configurations as also reported in previous studies in the literature. The occurrence and location of the distinct peaks should be discussed in future studies.

The findings of the study are only valid for the test site and site-specific tests are recommended in the final design of wave barriers. It is recommended that these wave barriers should be tested at different sites under different test conditions such as an inundated form of rubber chip barrier due to groundwater table or rainfall, under different types of loading such as impact or passage of a continuous source in future studies.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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