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Ground Vibrations Isolation By PC Wall-Piles

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ABSTRACT

This paper presents the results of a series of experiments conducted on a PC wall-piles barrier. That barrier was built alongside a road passing through some sensitive sites, to assess its effectiveness in isolating vibration caused by running trains and dropping a weight. Then the effectiveness of PC wall-piles for controlling ground vibrations is discussed. Field measurements were performed for 5 cases having different types of PC wall-piles. The simultaneous measurement of vibration was performed at several selected points on the ground. Finally, a method for estimation of vibration reduction by PC wall-piles was developed, being based on wave penetration theory.

The major findings from this series of experiments are as follows:

1. Vibration level as registered on the off-side of the PC wall-pile barrier was found to be 5 to 7 dB lower than that recorded at the site with no such barrier.
2. The maximum isolation effectiveness was obtained in the case of hollow PC wall-piles.
3. The theoretical results using the wave penetration theory showed a good agreement comparing with the field tests.

KEYWORDS

Damping, Ground Vibration, Isolation Method, PC wall-pile, Site Investigation, Wave Propagation

INTRODUCTION

Ground vibration arising from the recent advent of high-speed railways and motor-ways as well as large-scale factory installations and heavy construction machinery has become a serious problem causing substantial damages to the buildings and peace of mind of the inhabitants as well as causing problems for a variety of precision equipment in their neighbourhood.

Under the circumstances, legislation called the "Anti-Vibration Law", the first of its kind in the world, was enacted in Japan in June, 1996. In addition, the "Environment Standard Law", was put into effect as of November, 1993. This law declared that "vibration pollution", defined as such phenomenon arising from vibration that may adversely affect the physical and mental health of the people as well as their living environment over a considerably large area around the source of such vibration, should be kept at bay. With the enactment of these laws, vibration issues have acquired an important status in the agenda of the administration.

However, effective steps can not be said to have been taken to curb ground vibration. A case in point demonstrating how critical such issues are is found in the area along the Hanshin High-Speed Motor-way running through towns and cities in southern part of Hyogo Prefecture in western Japan that were devastated by the Great Kobe Earthquake two years ago. Complaints of vibration caused by the land vehicles passing through the reconstructed Motor-way are frequent from people living along the road as they are now more sensitive to ground vibration than before the earthquake.

Various measures might be taken to check ground vibration at its source, at somewhere along the path through which it propagates, or either at its receiving end. In terms of economy and other conveniences, however, the most effective way to check such ground vibration seems to be reflecting, dispersing or otherwise diffracting such vibration by constructing a barrier of some sort between its source and the receiver.

It was Barkan [1962], Dolling [1970], Woods [1968] et al. who have developed a series of studies on the effectiveness of an open trench to isolate ground vibration by conducting a series of in situ experiments. Barkan and Dolling produced some guidelines for designing such trenches under a particular set of conditions. Woods proposed two distinct systems to isolate ground vibration, one being active isolation to be applied near the source of vibration and the other passive isolation which is effective if applied farther away from such source and near the receiver. Having defined that an open trench constituting an active barrier could be regarded as effective if the level of vibration was reduced by 75 % (12dB) at a point 10 times the Rayleigh wave length away from such trench. He further suggested that its depth must at least be 0.6 time the wave length of the vibration to achieve such effectiveness. With respect to an open trench located at a distance between 2 and 7 times the Rayleigh wave length from it and therefore regarded as being an passive barrier, he pointed out that its depth should be over 1.3 times the Rayleigh wave length for it to be similarly effective.

Through a series of experiments to passively isolate vibration by using a rigid wave barrier, Haupt [1977, 1981] demonstrated that its cross section, as normalized in terms of Rayleigh wave length, is one of the most critical factors to its effectiveness. This view, through holds true with barriers made of rigid bodies, is not applicable to those composed of soft materials. However, no plausible explanation has been brought forward for this.

It was De Cock and Kegrand [1991] who developed a new type of wave barrier consisting of a gas cushion enclosed in a frame covered with a geo-textile, its major feature being that it can easily be constructed into ground to a depth as great as 6 to 12 m. They claim to have verified that the barrier is capable of reducing vibration by as much as 60 to 90 % over a wide range of frequencies.

Al-Hussaini and Asmad [1991] conducted a study by using a bi-dimensional BEM algorithm applying thereto high order elements. Whereby, having assumed the ground to be a visco-elastic half space having either a homogeneous or an isotropic laminar structure, they demonstrated the effectiveness of a rectangular trench either open or filled-in as being a practical barrier capable of passively isolating a source emitting a vibration having vertical harmonic wave.

ON-SITE EXPERIMENTS

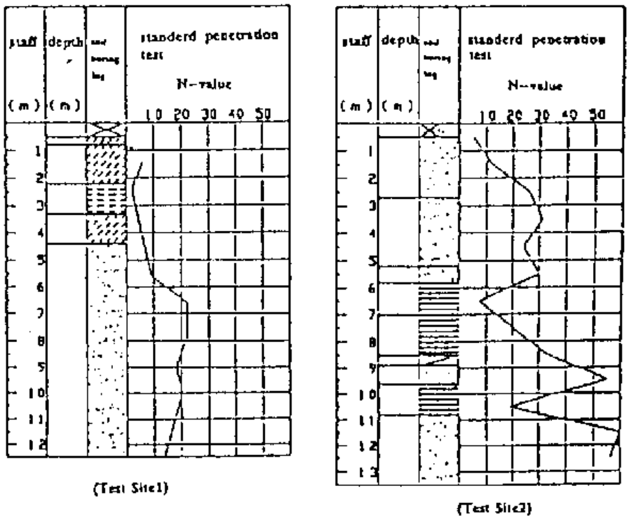
Test sites and soil conditions

Five test sites, three in Aichi prefecture. one in Gifu prefecture and another in Osaka prefecture, at each of which a row of piles had been installed, were chosen for the field experiments. Their identification numbers and exact locations are shown in Table 1 along with the main purpose of the barrier built at each site as well as the source of vibration involved.

Table. 1 Test site and condition

Test site	site name	purpose of construction	source of vibration
1	Ooe	road construction	freight truck
2	Hozumi	road construction	freight truck
3	Ichinomiya	road construction	rammer-truck
4	Takahama	sheathing construction	rammer
5	Takatsuki	sheathing construction	rammer

Boring logs as obtained at respective sites are shown in Fig. 1. From these boring logs, it can be seen that at Test Site 1 the soil is composed of a silt layer containing sand and gravel having an N-value between 2 and 4 from the ground surface to a depth of 6 m, followed by a soft silt layer with a N-value of 1 to a depth of 13 m. The soil at Test Site 2 is silt with an N-value of 2 to 3 to a depth of 9.6 m and below that depth it is gravel having an N-value of over 40.



(Test Site1)

(Test Site2)

Fig. 1 Boring log of the test site

Experimental set up

By using a vibration level meter, the vertical component of vibration acceleration level (VAL) dB was measured. The VAL is expressed in terms of $20\log A/A_0$. Where $A(m/s^2)$ is the effective value of vibration acceleration value, and $A_0=10^{-5}(m/s^2)$ is the reference acceleration value. These vibration source are a passing freight train, a large truck, and a free falling weight such as that used for a standard penetration test, at respective Test Sites. In the latter case the weight of the rammer was 63.5 kgf and the height from which it was let fall was varied in four steps; 25, 50, 75 and 100 cm. Data were magnetically recorded into a data recorder.

The experimental set up is shown in Fig. 2 along with the cross sectional view of the Test Site 1 and 2. A number of pick-ups were installed on the ground surface along a line perpendicular to the PC wall-pile barrier at its middle point, except at Test Site 3 where the line along which vibration was measured was located at one edge of the barrier.

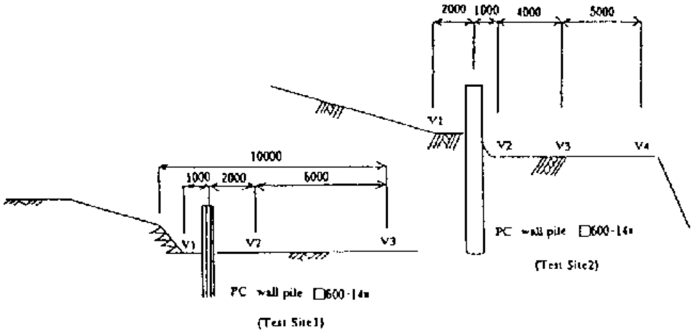


Fig. 2 Cross sectional view of the test site

Measurement was conducted under five and three different conditions at Test Site 4 and Test Site 5 respectively, the difference being shown in Tables 2 and 3 with a view to determining the effect of the filling in the hollow piles and/or grouting the spaces between piles, on their performance to isolate vibration.

Table. 2 Measurement condition (Test Site 4)

Filling condition	Case 1	Case 2	Case 3	Case 4	Case 5
Grouting of space	exist	nothing	exist	nothing	without PC pile
Mortaring of hollow	exist	exist	nothing	nothing	

Table. 3 Measurement condition (Test Site 5)

case 1	case 2	case 3
with PC pile (mortaring of hollow)	With PC pile (hollow)	Without PC pile

Details of the PC wall-pile barriers and their installation method

The PC wall-piles used to build the barriers herein were prestressed square type piles with a central hole. Their details are shown in Table 4; cross·section was 600 mm X 600 mm, length, 14 m, and diameter of the hole, 400 mm. These piles had been longitudinally stressed to 80 kgf/cm^2. The barriers were built by installing these piles in succession along a line by using the method known as "boring through central hollow", which is being widely applied in driving precast concrete piles. While the piles were being driven, care was taken to accurately aline them and to make sure that they were closely fitted to one another.

Table. 4 Standard dimensions

Outer Diam (mm)	Class	PC Wire			Area of Concrete (cm^2)	Moment of Intertia of Concrete (cm^4)	Equivant Section Moduls (cm^3)	Calculated Bending Moment	
		Diam (mm)	Numbers (pcs)	Area (cm^2)				Cracking (t·m)	Ultimate (t·m)
600	A	9.0	16	10.18	2,186 (3,643)	904,900 (1,508,000)	31,270 (52,110)	28.1	40.8
	B	10.0	30	23.56			32,370 (53,950)	42.1	79.5
	C	11.2	30	30.00			32,980 (54,960)	49.5	95.9

RESULTS AND ANALYSIS OF THE EXPERIMENT

Effect of the barriers to isolate vibration caused by a passing freight train at Test Site 1 and 2, and that generated by a free falling weight at Test Site 3, 4 and 5 were determined. At both sites measurements were taken at the moment when the vibration level reached a maximum while a freight train was passing on the railway track behind the barriers. Maximums and arithmetic averages were determined of the vibration level for four to five such events. Tables 5 and 6 show the results as obtained at Test Site 1 and 2 respectively. Comparing the vibration level at a distance of 10 m from the barrier with that as registered without such barrier at the same points, it can be noted that the barrier reduced the level by 5 to 7 dB.

Table. 5 Maximum and average values of vibration level(dB) (Test Site 1)

Position	Front of wall	2m	8m
With barrier	69(66)	51(49)	49(49)
Without barrier	67(67)	66(65)	58(55)

Table. 6 Maximum values of vibration level (dB) (Test Site 2)

Position	Front of wall		2m	11m
With barrier	67	67	53	55
Without barrier	68	62	60	60

Effect on vibration by a free falling weight

Experiments were conducted by letting a weight fall from a height of 100 cm as it had been observed that the height from which it was let fall did not noticeably affect the level of acceleration in the vibration it produced. Data thus acquired were plotted in Fig. 3 to show how the vibration level decreases with distance at Test Site 3 by the presence of the barrier as compared to that observed without barrier. Similar experiments were subsequently conducted at Test Sites 4 and 5 with the hollows of the piles filled-in and/or the joint between them ground, and the data taken are shown in Fig. 4.

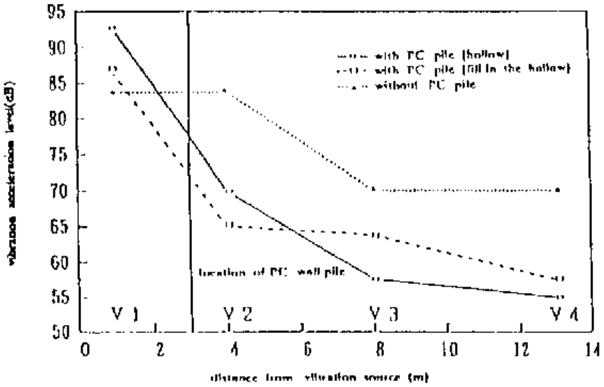


Fig. 3 Comparison of vibration value with distance

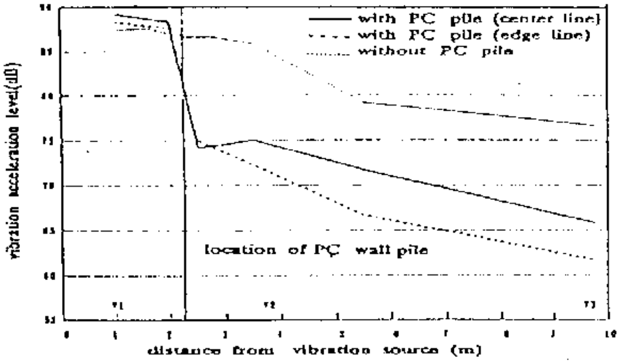


Fig. 4 Comparison of vibration value with distance

Observing the data taken at Test Site 3, the vibration level along the line normal to the barrier at its middle point is seen to have reduced by 7.5 to 13 dB over a distance from just behind the barrier to a point 4 m away from it. Along the line perpendicular to the barrier at its one edge, the decrease was about 11 to 16 dB over the same interval. It is interesting to note that the reduction in vibration level by the barrier was greater along the latter line than along the former, as this phenomenon is contrary to what might be assumed if one takes into account the diffraction of the waves it can also be seen that the level was further reduced by about 4 to 7 dB over the same distance by filling the hollow of the piles though this can not simply be generalized as the magnitude of such reduction varied with distance from the barrier. The additional effectiveness of the barrier can be accounted for by a decrease in its void ratio by the filling in the hollows of the piles. From the data taken from the experiments conducted at Test Site 4, where the hollows in piles and/or joints between them were filled or grouted or left open providing four different cases in addition to the case of no-barrier (see Table 2), the effectiveness was observed to be optimal with Case 1 (hollows filled and joints grouted) followed by Case 2, Case 3 and Case 4 (hollows not filled, joints not grouted) in this order.

SUMMARY CONCLUSION

Summarized in Fig. 5 are the results from the experiments conducted at Test Sites 1 through 5 as well as data that had been reported elsewhere indicating the reduction in the level of vibration with distance from a barrier made of PC wall-piles.

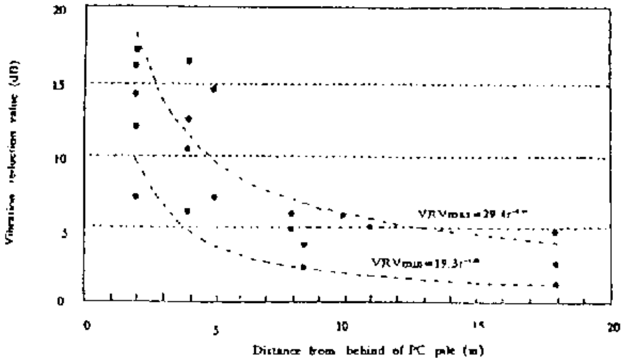


Fig. 5 Vibration reduction value with the distance behind of PC pile

It can be noted that (i) the reduction in the level of vibration by a PC wall-pile barrier from that registered without such barrier exponentially decreases with distance from the barrier as represented by the empirical formula shown in the same figure,

$$VRV_{max} = 29.4r^{-0.99} \qquad (1)$$
$$VRV_{min} = 19.3r^{-1.02}$$

(ii) at a point just behind the barrier, the reduction was as large as 10 dB but it decreases to 5 dB at about 10 m away from the barrier , and (iii) additional reduction in vibration level by filling in the hollow of a PC wall-pile barrier has not clearly been identified enough data not being available at the moment.

DISCUSSION

The ratio between the amplitude of a wave as registered on the up stream and that on down stream of an isolation barrier installed into the ground as shown in Fig. 6 can be expressed according to the prevailing wave penetration theory.

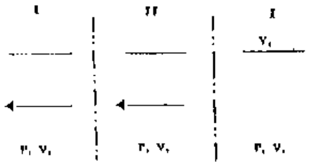


Fig. 6 Ground model of wave penetration

By transforming formula into a logarithmic function, reduction in vibration by the barrier can be expressed by the following equation:

$$20\log_{\text{r}}=12-20\log\{(1+\alpha_{12})(1+\alpha_{23})-(1-\alpha_{12})(1-\alpha_{23})\}$$
$$-10\log 2\ (1-\alpha_{12}{}^{2})(1-\alpha_{23}{}^{2})\cdot\cos(2H\omega/100Vs)\ (\text{dB}) \qquad (2)$$

where ρ_1, ρ_2: Densities of the medium I and medium II respectively V_1, V_2: S wave velocities at which wave is transmitted through medium I and medium II respectively H: Thickness of the barrier α_1, α_2: Impedance ratio

Shown in Fig. 7 is the reduction in vibration level as calculated according to Equation (2) using data taken from the experiment conducted on the PC wall-pile barrier installed at Test Site 4 where the hollows in the piles composing the barrier had been filled and the joints between them grouted (See Table 2, Case 1).

The continuous line in Fig. 7 corresponds to the case where Vs was taken to be 100 m/s while the broken line indicates the result as obtained by assuming Vs to be 350 m/s. Data shown with symbol (·) represent the reduction in vibration at a point 1.9 m away from the barrier as obtained from a frequency analysis conducted over 1/3 octave band on the results from the experiment by using a FFT analyzer. It can be observed that the data from the latter analysis is in good agreement with the calculated results all over a range of frequency between 1 and 80 Hz, except at around 32 Hz.

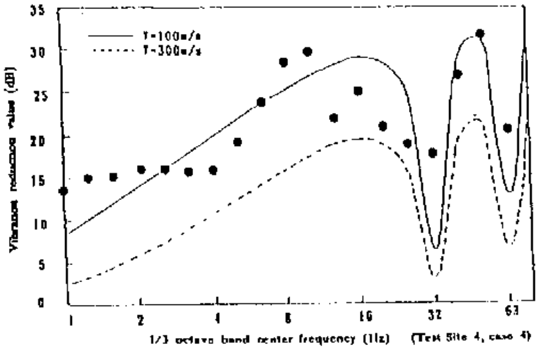


Fig.7 Comparison of vibration reduction values with measured values and theoretical ones (Test Site 4, case 4)

Similar calculations were conducted with the data taken at Test Site 3 to work out the reduction in vibration level according to the wave penetration theory. Combined reduction was then calculated by further using Equation 3 representing the vibration reduction factor as worked out through an experiment using a model, assuming that the hollows in a PC wall-pile barrier are an air trench. In these calculations, Vs was assumed to be 200 m/s and 450 m/s at Test Site 3.

$$Ar = e^{-2.35H/\lambda r} \qquad (3)$$

where Ar: Amplitude reduction factor, H: Depth of trench, λ r: Rayleigh wave length.

Shown in Fig. 8 are the results thus calculated as well as those obtained by experiment. Here, too, a good agreement is seen between the calculated and experimental results over a range between 1 and 80 Hz, indicating that the formula may be used to assess the reduction in vibration level by a barrier composed of PC wall-piles over that range of frequency. The accuracy in the calculation could have been better had actually measured been S wave velocities been used instead of those estimated from blow counts from boring tests as was the case with this study.

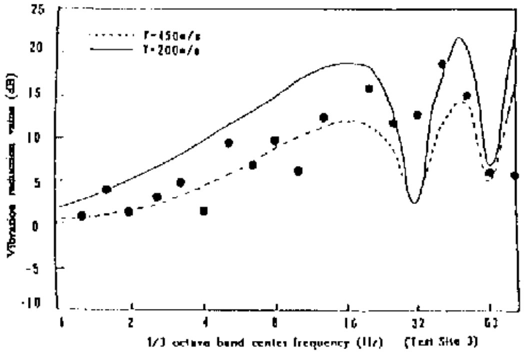


Fig.8 Comparison of vibration reduction values with measured values and theoretical ones (Test Site 3)

COMPARISON WITH RESULTS OF PAST WORKS

Having analyzed the effect of such a rigid body as a concrete wall built into ground to isolate vibration using a FEM technique, Haupt produced a graphical representation of the relationship between the vibration reduction factor achieved by such a body and its cross section as $S=BT/\lambda r^2$, normalized in terms of the Rayleigh wave length.

This relationship is shown in Fig. 9 along with the results obtained through this study, the latter data being plotted with symbol (·). The Rayleigh wave velocity herein referred to was determined by using the relationship between S wave velocity and the average N value over the interval from ground surface to a depth at which it had shown a sudden increase during a boring test, using: $Vs=92N^{0.239}$ (4) where Vs : S wave velocity (m/s), N: N-value as obtained through a standard penetration test and, $Vr=0.92Vs$ (5) Poisson's ratio was assumed to be 0.25.

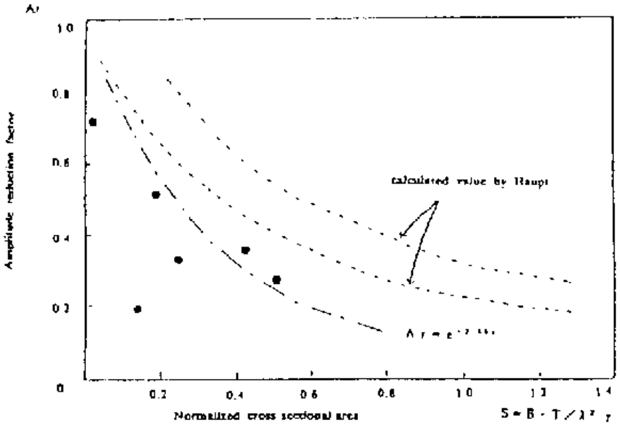


Fig. 9 Amplitude reduction factor from tests on solid barriers

In Fig. 9 it can be observed that the reduction factor achieved in this study by installing a barrier made of hollow PC wall-piles is located below the curve representing the calculated result by Haupt indicating that the former offers a greater reduction ratio than a rigid wave barrier. The better performance of PC wall-pile barrier may be attributed to the combined effect of the piles themselves capable of partly isolating the vibration by acting as rigid bodies and the hollows in them which contributed to its further reduction. If this is the case, the difference between the curve showing the lower limit of the results as presented by Haupt and the data as measured in this study can be taken as representing the effect of the hollows in the piles composing the PC wall-pile barrier herein dealt with.

Ahmad et al. [1991], having analyzed the effect on such barriers as underground concrete wall and gas cushion presented a relationship between their Ar values (reduction factor) and distance from such barriers as shown in Fig. 10.

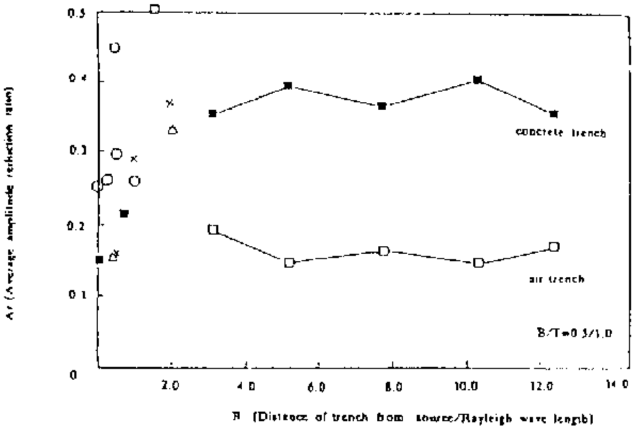


Fig. 10 Amplitude reduction factor depending on distance R

Corresponding data as measured in the present work were plotted on the same diagram for comparison. It is natural enough that these data stand, as can be noted, between the curve representing the reduction factor of the concrete wall and that of the gas cushion as presented by them. Although the former data are seen to be clustered at the extreme left in the diagram as they had been taken over relatively small distances from the barrier. This provides further that a vibration barrier comprising hollow PC wall-piles combines the effect of a rigid wall and hollows. From the above, and considering the ease with which it can be built, the safety and economy it provides, it can be concluded that a PC wall-pile barrier may offer a highly effective means of isolating ground vibration.

CONCLUSIONS:

In this paper the effect of a new type of barrier made of PC concrete wall-piles was addressed. Results were presented of in situ experiments carried out using PC wall-pile barriers that had been built at five different localities. Reference was made to a method to calculate the reduction in vibration by a PC wall-pile barrier in accordance with a wave penetration theory. Results from the present study were compared with those calculated by using a method reported elsewhere. From the study it was found that:

1. The PC wall-pile barriers were found to be capable of reducing vibration level by 10 to 15 dB at a point just behind such a barrier and about 5 dB at 10 m away from it, the reduction being exponentially related with the distance from such barrier.
2. The reduction decreased by 4 to 7 dB when the hollows of such piles were filled in.
3. By using the above mentioned theory along with an empirical formula for open trenches, reduction in vibration by a barrier made of filled-in PC wall-piles can be calculated with a reasonable accuracy over a range of frequency between 1 and 80 Hz.
4. As verified through the present study, the effect of a barrier composed of hollow PC wall-piles to isolate vibration is in between that of a rigid barrier such as concrete wall and that of a gas cushion represented by use of an open trench, these latter effects being determined through a theoretical analysis as reported elsewhere.
5. From the conclusions listed above, the performance of the PC wall-pile barriers can be attributed to the combined effect of the piles themselves composing a rigid body and that of the hollows in them acting as a gas cushion.

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