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Field experiment and numerical study on active vibration isolation by horizontal blocks in layered ground under vertical loading

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ABSTRACT

In this paper, a series of field experiments were carried out to investigate the active vibration isolation for a surface foundation using horizontal wave impedance block (WIB) in a multilayered ground under vertical excitations. The velocity amplitude of ground vibration was measured and the root-mean-square (RMS) velocity is used to evaluate the vibration mitigation effect of the WIB. The influences of the size, the embedded depth and the shear modulus of the WIB on the vibration mitigation were also systematically examined under different loading conditions. The experimental results convincingly indicate that WIB is effective to reduce the ground vibration, especially at high excitation frequencies. The vibration mitigation effect of the WIB would be improved when its size and shear modulus increase or the embedded depth decreases. The results also showed that the WIB may amplify rather than reduce the ground vibration when its shear modulus is smaller or the embedded depth is larger than a threshold value. Meanwhile, an improved 3D semi-analytical boundary element method (BEM) combined with a thin layer method (TLM) was proposed to account for the rectangular shape of the used WIB and the laminated characteristics of the actual ground condition in analyzing the vibration mitigation of machine foundations. Comparisons between the field experiments and the numerical analyses were also made to validate the proposed BEM.

1. Introduction

Man-made vibrations induced by machines, traffic, blasting, pile driving, etc. have become public nuisance annoying nearby structures, underground pipelines, sensitive electronic equipment and inhabitants [1–4]. To eliminate or reduce such disturbances, several kinds of countermeasures have been proposed in the past. The first kind of countermeasure is to reduce the vibration magnitude of the source, such as adjusting the frequency contents of the source, changing the location and direction of the source or installing dampers under the source. The second kind of countermeasure is to limit the magnitude of vibrations input into the structures, such as increasing the damping of the structure by installing additional dampers or other base-isolation systems. Beside the above two kinds, another possible kind of countermeasure is to modify the dynamic transmitting behavior of local subsoil via wave diffraction and scattering by installing wave barriers at suitable locations in the wave propagation path between the source and the structure. The commonly used wave barriers include open or in-filled trenches [5–11], rows of solid piles [12–16] or tubular piles [17], and gas mattresses [18,19]. For barriers installed near the vibration source, they are usually classified as active or near field vibration isolation. On the other hand, for barriers installed far from the source and close to the structure, they are classified as passive or far-field vibration isolation. One common characteristic of these wave barriers is that their dimension in the vertical direction (or depth) is significantly larger than those in the other directions. It is well recognized that the depth of the above barriers is the most crucial factor influencing the wave mitigation effect. Generally, depth of one Rayleigh wavelength at least is required in order to achieve a satisfactory vibration isolation effect. However, the Rayleigh wavelength generated by the man-made low frequency vibration can be very long. Therefore, in such cases, it is difficult to implement successfully in practical constructions due to soil instability, underground water, foundation requirements, cost and other issues.

Except for the above vertically installed wave barriers, another promising horizontally installed wave barrier called wave impedance block (WIB) has drawn increasing attentions in vibration isolation of machine foundations, as shown in Fig. 1. The principle

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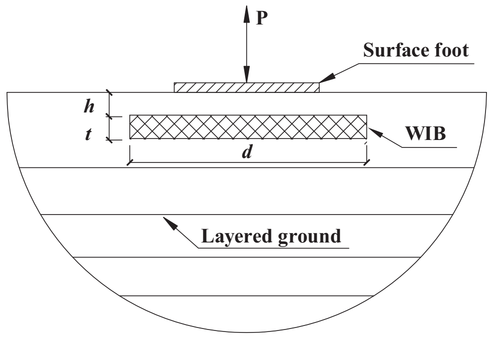

Fig. 1. Schematic of WIB in layered ground for vibration isolation.

of the WIB is to modify the wave propagation regime of the ground by introducing an artificial horizontal stiffened layer. In other words, the wave transmission regime in the ground depends on the relationship between the excitation frequency of the source and the cut-off frequency of the overlaying soil above the WIB. When the exciting frequency is higher than the cut-off frequency, wave will transmit. Otherwise, wave transmission will be prevented [20,21].

In the past, theoretical investigations on WIB have been carried out with numerical methods such as boundary element method (BEM), finite element method (FEM) as well as their combination, and concentrated on its impeding effect on the vibration exerted by foundations. Chouw et al. [22] first analyzed the active and passive vibration isolation using WIB with a 2D BEM in the frequency domain. Their findings indicated that increasing stiffness of WIB improves the screening effectiveness. Moreover, WIB does better in impeding low frequency vibration than in-filled trench. Following the pioneer work by Chouw et al. [22], Takemiya and Jiang [23] investigated the vibration isolation effects of WIB under loadings exerted by pile group embedded in a homogenous ground with FEM. Takemiya and Fujiwara [24] further explored the performance of WIB for vibrations due to sudden excitations using a 2D BEM in the time domain. Stamos et al. [25] investigated the vibration isolation effect of an open or filled trench and a stiff plate embedded in the soil between the road surface and the tunnel for a road-tunnel traffic system using BEM in frequency domain and FEM–BEM in time domain under plain strain conditions. Antes and von Estorff [26] investigated the isolation effects of WIB with varying stiffness using 3D BEM in the frequency domain and a combination of 2D BEM and FEM in the time domain. After that, several researchers began to introduce layered ground into WIB study, instead of homogenous ground. For example, Peplow et al. [27,28] employed the boundary integral equation method to study the active screening effectiveness of WIB in a double-layered ground. More recently, Xu et al. [29] invoked an integral equation and transfer-matrix formulation to study the wave mitigation effects of 2D WIB for the vibration due to a harmonic strip load on the stratified subgrade surface.

With the rapid development of high-speed rail, subway and light rail, many researchers began to exploit WIB to screen the vibrations induced by tracks. Madshus et al. [30] and Kaynia et al. [31] studied the vibration induced by the high-speed railway and analyzed the vibration isolation efficiency of a WIB-like stiff plate buried beneath the ballast using FEM incorporated with a horizontal non-reflect boundary in the frequency domain and time domain. Andersen and Jones [32] adopted combined FEM–BEM to study the effect of grouting on the isolation of track vibrations in tunnels, in which the stiffened soil worked as a WIB. Peplow and Finnveden [33] investigated the isolation effects in the near field by WIB against vibrations below 200 Hz with a 2D spectral FEM. More recently, Li et al. [34] compared the vibration isolation effects of entity WIB, honeycomb WIB, open trench and diaphragm wall against the low frequency vibrations induced by high-speed railway. However, in the previous theoretical studies, little attention has been paid to the influences of WIB geometrical, material properties and embedded depth on the wave mitigation effect in a multilayered ground. Therefore, Gao et al. [35–37] proposed a 2D plain-strain model and a 3D axisymmetric model with the aid of a semi-analytical BEM integrated with the fundamental solution derived by the thin layer method (TLM). Based on these two models, the influences of the WIB geometrical and material properties including diameter, shear modulus and embedded depth on the screening effectiveness in a double-layered ground and a Gibson-type ground were extensively investigated and several useful conclusions were drawn. Strictly, however, the 2D model and the 3D axisymmetric model are appropriated only for strip WIB and circular WIB, respectively. Nevertheless, the actual shape of WIB is usually rectangular and it is a general 3D problem, especially for the vibration isolation of machine foundations. Moreover, the actual ground was usually multilayered, instead of assumed homogeneous or double-layered. Most importantly, these theoretical studies usually were not verified by experiments.

So far, though considerable theoretical achievements in WIB research have been made, very limited experimental works have been performed to investigate the vibration reduction effect of WIB and validate these theoretical findings. Kratzig and Niemann [38] reported the field tests of using horizontal WIB as an active or passive vibration isolation element for the surface foundation subjected to harmonic vertical excitations. The test results showed that the WIB can effectively reduce the vibration amplitude of the foundation, especially the vertical component. They also showed that WIB was effective to reduce the vibration in centrifuge model tests and holographic interferometry tests. Takemiya et al. [39] used the stiff honeycomb soil-columns formed by the soil improvement techniques under a road as a horizontal placed honeycomb WIB (HWIB) and studied its vibration isolation effect. Their results indicated that the WIB can reduce the traffic induced vibration. Besides the horizontal placed WIB, Takemiya [40] also successfully applied the HWIB which was vertically installed near the pile foundations of a high-speed train viaduct for vibration mitigation. Furthermore, he extended the HWIB by filling the precast honeycomb cells with tire shreds [41–44], which combines the wave scattering effect by stiff cell walls and the energy dissipation by fill-in tire shreds, and investigated the vibration mitigation efficiency under different load conditions by a series of field tests. Nevertheless, little attention was paid to the influences of WIB geometry, material properties (i.e. stiffness), embedded depth and the characteristic of the vibration (i.e. frequency) on the vibration isolation in these tests, although these factors will definitely affect the vibration isolation effect and the design of WIB in practice.

In this paper, a series of field experiments were carried out to investigate the vibration isolation effect of a horizontal placed rectangular WIB in multilayered ground under vertical excitation induced by a vibrator. The amplitude of vibration at different distances to the source was measured to evaluate the degree of vibration reduction. The effects of the WIB geometry, the embedded depth and the shear modulus of the WIB on the vibration reduction were also systematically examined under different loading conditions. Meanwhile, an improved 3D semi-analytical BEM combined with TLM was proposed to account for the rectangular shape of the used WIB and the laminated characteristics of the actual ground condition. Furthermore, comparisons between the field experiments and the numerical simulation were made to validate the proposed BEM and possible reasons were also given to explain the observed discrepancy.