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Numerical study on the active vibration isolation by wave impeding block in saturated soils under vertical loading

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ABSTRACT

Dynamic response in a saturated porous medium (i.e. two-phased medium) is significantly different from the commonly assumed single-phased elastic medium in vibration analyses. To investigate the ground vibration isolation by wave impeding block (WIB) in saturated layered soils under vertical loading, an improved three-dimensional (3D) boundary element model is established for analyzing the soil-foundation-WIB interaction problem. The equations of boundary element method (BEM) for saturated and layered soils were deduced using fundamental solution (Green's function) based on thin layer method (TLM), in order to account for the lamination characteristics of the ground. The vibration screening effectiveness of WIB with different thicknesses, equivalent diameters, shear module and embedded depths were systematically investigated and the results were compared with those in a single-phased elastic soil. The results show that the WIB can effectively reduce the vibration amplitude in the saturated ground and its effectiveness increases with increasing shear modulus, equivalent diameter, thickness, and decreasing embedded depth of the WIB. In addition, a significant amplification of the vibration is observed in the saturated soil when the dimensionless embedded depth is larger than or the dimensionless thickness is smaller than a threshold value.

1. Introduction

Ground vibrations induced by the dynamic loading (e.g., the traffic loading and dynamic machine foundations) have become public nuisances and engineering concerns. To eliminate or reduce such ground vibration, several vibration isolation measurements have been proposed, including the open or filled trench [1,2], rows of wave barrier piles [3,4], and wave impeding block (WIB).

Chouw et al. [5] firstly found the vibration screening phenomenon of bed rock when analyzing the vibration transmission in the soil above bed rock under a harmonic line loading. The bed rock can block the vibration propagation when the vibration frequency is lower than a threshold value (i.e., the cut off frequency). Chouw et al. [6] and Schmid et al. [7] then suggested placing an artificial bed rock called "wave impeding block" (WIB) under the vibration foundation to screen the low frequency vibrations in the wave propagation regime, as shown in Fig. 1.

After that, numerous studies have been conducted on the vibration isolation effectiveness of WIB in homogenous soils under different excitations using different methods. Schmid et al. [7] analyzed the active and passive vibration isolation of WIB by a two-dimensional (2D) boundary element method (BEM) in the frequency domain. Takemiya and Jiang [8] studied the vibration mitigation of WIB under the excitation of group piles in a homogeneous foundation by symmetric and asymmetric finite element method (FEM). Takemiya and Fujiwara [9] further analyzed the vibration mitigation of WIB under an impulse excitation by 2D BEM. Antes and Estorff [10] studied the influence of stiffness on the dynamic response of a block foundation under vertical loading by BEM-FEM. Andersen and Jones [11] explored the effect of soil grouting under the tunnel slabs on the low frequency vibration isolation by coupled FEM and BEM. Steenbergen et al. [12] showed that the reinforcement of the soil under the rail reduces the low frequency vibration and the increase of bending stiffness of the track slab reduces the high frequency vibration. Although different analysis methods have been adopted, a consistent conclusion can be drawn that WIB is an effective vibration isolating technique for various kinds of excitation in homogeneous elastic soils. Furthermore, WIB has remarkable screening effectiveness for low frequency vibrations and reduces more near field ground vibration below the cut off frequency than the open or filled trench with the same dimension.

It is well agreed that wave propagation significantly depends on the

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Nomenclature

a_0	dimensionless frequency	T, t	dimensionless and dimensional thickness of WIB in Section 5
B	Skempton's pore pressure coefficient	u_i	displacement of the soil skeleton (i=1, 2, 3)
B_r, b_r	dimensionless and dimensional length of the surface footing in Section 5	α	Boit's effective stress coefficient
C	a parameter to determine ρ_a	β	a parameter related to seepage in Eq. (2).
D, d	dimensionless and dimensional equivalent diameter of WIB in Section 5	γ	fluid source
e	volumetric strain of the soil skeleton	ζ	volumetric change of the fluid
F_i	body force on the solid skeleton (i=1, 2, 3)	η	the generalized coordinate in TLM
$\mathbf{H}$, $\mathbf{G}$	interaction coefficient matrix formed in BEM in Eq. (30)	κ	coefficient of the permeability of the soil
h	thickness of the i^{th} soil layer	μ, λ	Lame's constants of the soil skeleton
H_b, h_b	dimensionless and dimensional embedded depth of the WIB in Section 5	μ_b	shear modulus of WIB
i	variable i (in italic font)	ξ	damping ratio of the soil
i	imaginary unit (in normal font)	ρ	density of the saturated soil
$\mathbf{I}$	unit matrix	ρ_a	apparent mass density of the saturated soil in Eq. (2)
k	wave number	ρ_b	density of WIB
K	bulk modulus of the soil skeleton	ρ_f	density of the fluid
M	dimensionless shear modulus of WIB	ρ_s	density of the soil skeleton
n_z	total number of thin layers	ν	drained Poisson's ratio of the soil
$\mathbf{N}$	shape function used in TLM	ν_u	undrained Poisson's ratio of the soil
p	pore-water pressure	ν_b	Poisson's ratio of WIB
q	flux of the fluid	ϕ	porosity of the saturated soil
R	Biot's poroelastic constitutive coefficient	$\boldsymbol{\xi}_m$	vector of the eigenvalues of the eigenvalue problem formed when solving TLM
t_i	traction of the soil skeleton (i=1, 2, 3)	$\boldsymbol{\Phi}_m$	matrix of the eigenvectors of the eigenvalue problem formed when solving TLM
		ω	circular frequency

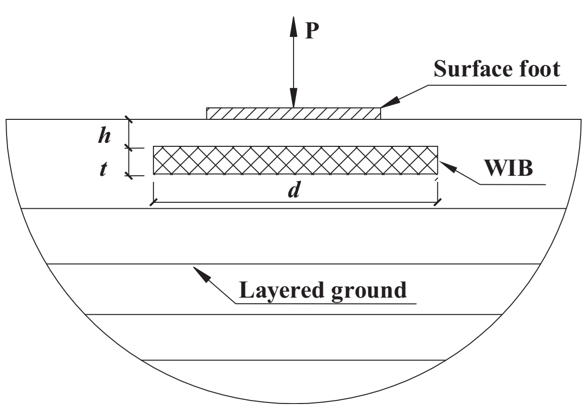

Fig. 1. Schematic of WIB in a layered ground for active vibration isolation.

soil properties, especially in layered ground where wave scattering and reflection exist on the interfaces of soil layers. Peplow et al. [13,14] studied the active vibration isolation of WIB in a double layered ground using boundary integration method. Peplow and Finnveden [15] investigated the near field vibration isolation of WIB in stratified layers using 2D spectral FEM. Gao et al. [16] carried out both experimental and numerical studies on the vibration isolation of WIB under harmonic vertical loading in a layered ground. Kaynia et al. [17] and Tan et al. [18] studied the vibration isolation of a rigid plate in ballasts under high speed train loading and subway train in the frequency domain, respectively. They found notable reduction of ground vibration along the rail line by the rigid plate. Takemiya [19–21] proposed an innovative countermeasure termed honeycomb WIB (HWIB) when exploring ways of reducing traffic induced vibrations. The results indicated that HWIB can significantly reduce the vibration amplitude in the ‘shadow zone’ against the source, and the vibration mitigation of HWIB was better than the conventional countermeasures.

It should be noted that all the above investigations were conducted in a single-phased elastic medium. However, the actual soil is a porous medium and usually saturated with water, especially when the groundwater table is high. It was found that the dynamic response in a saturated porous medium (i.e. two-phased medium) is significantly different from the commonly assumed single-phased elastic medium in vibration analyses [22–25] due to the coupling effect of water and soil skeleton (i.e. dispersion), especially when seepage existed [26,27]. Although researches on dynamic responses in saturated soils gained certain achievements, studies on the behavior of vibration isolation techniques in saturated soils are still very limited. Xu et al. [28,29] investigated the vibration isolation effect of pile rows embedded in a saturated half-space. Their results suggest that the vibration isolation effect of pile rows is better in saturated porous elastic medium than that in a single-phased elastic medium. The results also indicated that the pile needs to be impractically long in order to mitigate low frequency vibration which attenuates slowly and would cause severe vibrations in buildings adjacent to the vibration source.

In summary, though many studies have been performed on the vibration isolation effect of WIB using either experimental or numerical methods, none of them investigates the significance of the saturated porous soil on the vibration screening performance of WIB. Meanwhile, the previous studies just showed that the WIB does reduce the vibration, but how the geometry, embedded depth and material properties will affect the vibration isolation effect is not well investigated and understood. Hence, it is necessary to establish numerical models for WIB analysis in saturated soils and study the influencing factors on the WIB performance, which may provide useful guidelines for the design of WIB in practice.

In this study, an innovative boundary element method for layered saturated ground is established. In this method, the Green's functions, also named fundamental solutions are derived through the thin layer method (TLM) to account for the lamination characteristics of the natural ground. The established boundary element method is used to investigate the dynamic response of the soil structure interaction between a surface footing, WIB and saturated ground under vertical harmonic loading. The effects of the thickness, equivalent diameter,