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Anti-plane response caused by interactions between a dike and the surrounding soil

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ABSTRACT

This paper proposes a novel strategy for the investigation of displacement amplitude ($|u_y|$) near and along symmetric dikes comprising a trapezoidal structure with a circular-arc foundation when subjected to shear horizontal (*SH*) waves. Materials in the half-space dealt with two types of dike: (1) soft dikes, and (2) hard dikes. Modified transfinite interpolation (MTFI) was used to obtain the coordinates of nodes and determine the sequence of node numbering in the inner finite region, which included a dike and a semi-circular-arc annulus. MTFI was shown to overcome the difficulties involved in the meshing of irregularity. The proposed hybrid method, comprising finite element method and a Lamb series, was applied in conjunction with MTFI in order to study the effects of dike material, the incident angle of *SH* waves (θ), and a dimensionless frequency (η) on $|u_y|$. We briefly describe a closed-form solution to the problem of rigid semi-cylindrical foundations proposed in a previous study and then conducted a comparison of theoretical solutions and numerical results obtained using the proposed hybrid method.

In the case of soft dikes, the natural fixed-base frequency of the foundation was close to the quasi-resonance frequency (QRF), which resulted in a maximum value of $|u_y|$ ($|u_y|_{\max}$) at the top of the trapezoidal structure for various η. However, in the case of hard dikes, the $|u_y|_{\max}$ at the top of trapezoidal structure and in the dike foundation appeared at various QRF due to the fact that the movement of a hard dike is close to a rigid body motion. Energy absorption in a soft dike was shown to be superior to that of a hard dike, based on the fact that the shape of the deformed soft dike was more complex than that of the hard dike, and a number of displacement peaks observed inside the soft dike may be indications of damage within the dike that must be taken into account. Interestingly, the proposed hybrid method with MTFI provides a better understanding of the soil-structure interaction, compared with results obtained in previous studies.

1. Introduction

At the site of surface irregularities, such as a convex topography (hills or dikes), ground motion resulting from earthquakes can increase the amplitude of responses in the frequency domain. This phenomenon can be attributed to the scattering and diffraction of propagating waves, particularly standing waves in a finite region (such as hills or dikes). Developing an understanding of the mechanisms underlying the scattering of waves by surface irregularities is essential to the process of structural design. In case of a 2-D convex topography embedded in an elastic half-space, the scattering of waves in the half-space and the standing waves created by the convex topography must be considered simultaneously.

Unlike hills, dykes require that researchers take into account differences in the material properties, such as density (ρ) and shear modulus (μ) between the dike and ground, as well as boundary conditions at the interface. Thus, most previous reports have focused on the scattering of shear horizontal (*SH*) waves induced by hills. For example, the wave function expansion method (WFEM) has been proposed as a means of analyzing the scattering of *SH* waves induced by various types of hill, such as cylindrical hills in circular-arc cross-section [1], semi-cylindrical hills [2], circular-arc hills [3], shallow semi-elliptical hills [4], and deep semi-elliptical hills [5]. The boundary element method was also used to decipher the scattering of *SH* waves by triangular-curve-shaped hills [6], semi-circular hills [7], and semi-elliptical hills [8].

A number of previous studies have reported on the soil-structure interaction between the foundation of a shear wall (or dike) and the

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ground. Some of structures that have been studied include rectangular shear walls with a semi-circular rigid foundation [9], rectangular shear walls with a semi-elliptical rigid foundation [10], triangular dikes with a circular foundation [11], triangular dikes with a flexible circular foundation [12], and tapered shear walls with a semi-circular rigid foundation [13].

These studies assumed a rigid foundation in their investigation of the response of shear walls and the impact of *SH* waves on the ground [9,10,13], which led to the conclusion that the movement of a rigid foundation is independent from the incident angle of *SH* waves (θ). A flexible foundation was adopted in these investigations into the response of a triangular dike at a low dimensionless frequency (η) in the range from 0.0 to 1.0 [12]. No previous studies have reported the use of numerical or theoretical methods to study the response of dikes with a flexible foundation impinged by *SH* waves. Nor have previous researchers investigated the soil-structure interaction between a flexible foundation and the ground at a higher η (such as $\eta > 1.0$).

This study presents a novel, systematic strategy by which to investigate the scattering of *SH* waves induced by a dike embedded in an elastic half-space. The dike studied herein includes a symmetric trapezoidal structure on the ground with a circular-arc foundation under the ground (Fig. 1). This study also introduced modified TFI (MTFI) for the mapping of two arbitrary finite domains comprising a symmetric dike and partial region of elastic half-space (physical region) into two-unit square domains (logical region). This approach makes it possible to determine the coordinates of nodes and the sequence of node numbering in the physical region. We then developed a hybrid method comprising FEM and wave function based on Lamb series to obtain a numerical solution to the problems proposed in this study. We also investigated how θ and η of *SH* wave and the material properties of the dike influence the displacement of the dike and the neighboring region. The mechanisms underlying the natural fixed-base frequency (NFBF) of the foundation were also investigated.

Two comparisons were conducted to evaluate the proposed method: 1) Under the assumption that the ρ and μ values in the dike are identical to those in the elastic half-space, we sought to determine the displacements of the dike and the neighboring region in order to compare results with those reported by Shyu and Teng [14]. 2) We calculated the values of NFBF at the intersections between the foundation of the dike and the ground (such as points P and T shown in Fig. 1) to enable a comparison with those obtained using the closed-form solution by Trifunac [9]. The derivation of the closed-form solution is briefly described in Section 3.

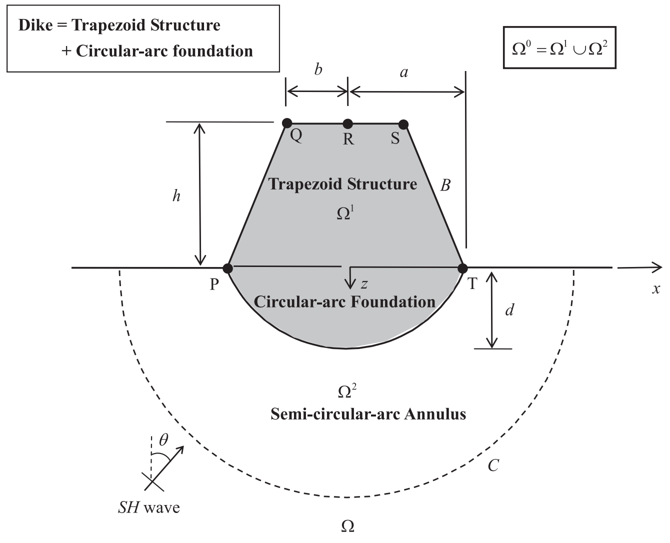

Fig. 1. Schematic illustration of inner finite region (Ω^0) including a symmetric dike.

Table 1
Test conditions applied to symmetric dikes.

	h/a	b/a	d/a	μ^1/μ	ρ^1/ρ	C_s^1/C_s	M_o/M_s	M_b/M_s
Case 1	1.000	0.500	0.500	0.167	0.667	0.500	0.667	1.431
Case 2	1.000	0.500	0.500	6.000	1.500	2.000	1.500	3.219

2. Numerical model

2.1. 2-D symmetric dike

This study investigated a symmetric dike embedded within an elastic half-space on the *x-z* plane excited by a unit-amplitude plane *SH* wave (perpendicular to *x-z* plane) with θ and circular frequency (ω). This elastic half-space was divided into two regions: (1) an inner finite region Ω^0, which includes a symmetric dike (Ω^1) and a semi-circular-arc annulus in the half-space (Ω^2); and (2) an outer infinite region Ω, in which the boundary (C) between Ω^0 and Ω is a semi-circle.

The symbols a, b, and h in Fig. 1 represent the half-width at the bottom, the half-width at the top, and the height of trapezoidal structure, respectively. Furthermore, d represents the depth of foundation. Table 1 lists the dimensionless parameters for two types of symmetric dike: (1) soft dikes ($C_s^1 < C_s$), and (2) hard dikes ($C_s^1 > C_s$), in which $C_s = \sqrt{\mu/\rho}$ represents the wave speed in Ω as well as Ω^2, and $C_s^1 = \sqrt{\mu^1/\rho^1}$ represents the wave speed in Ω^1.

2.2. Governing equation for scattering of SH wave

The contributions to physical quantities from free and scattered fields are usually taken into account when addressing the problem of *SH* wave scattering induced by a symmetric dike. Accordingly, the traction (t_y) and displacement (u_y) in the y direction can be expressed as follows:

$$t_y = t_y^f + t_y^s \quad ; \quad u_y = u_y^f + u_y^s \tag{1}$$

where superscripts f and s represent the free field and scattered field, respectively. For the incidence of an unit-amplitude *SH* plane wave, the displacement in the free field (u_y^f) is produced by the combined effects of incident and reflected *SH* plane-waves, which produce a complex number, given as follows:

$$u_y^f(x, z) = 2\exp\left[i\omega\left(\frac{x\sin\theta}{C_s}\right)\right]\cos\left(\frac{\omega z\cos\theta}{C_s}\right) \tag{2}$$

The absolute value of u_y^f at the free surface (i.e., $|u_y^f(x, 0)|$) is 2.0.

Both u_y^f and u_y^s must satisfy the following governing equation of motion:

$$\frac{\partial\sigma_{xy}^{()}}{\partial x} + \frac{\partial\sigma_{zy}^{()}}{\partial z} + \rho\omega^2 u_y^{()} = 0 \tag{3}$$

In Eq. (3), the superscript of the blank parenthesis can be replaced with either f or s. The shear stresses $\sigma_{xy}^{()}$ and $\sigma_{zy}^{()}$ in terms of displacements are given by the following:

$$\sigma_{xy}^{()} = \mu^{()}\frac{\partial u_y^{()}}{\partial x} \quad ; \quad \sigma_{zy}^{()} = \mu^{()}\frac{\partial u_y^{()}}{\partial z} \tag{4}$$

The hybrid method in this study makes it possible to obtain the nodal displacement (u_y^0) in Ω^0 and u_y in Ω. Derivation of a matrix equation involves the selection of an appropriate functional followed by the implement of variation of the functional, which is further described in Section 2.3.

2.3. FEM coupling with wave function

Substituting 0 as the superscript into Eq. (3) changes the governing