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Modal analysis for kinematic response of flexible cantilever retaining wall

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Abstract

Seismic response of flexible cantilever wall retaining a semi-infinite viscoelastic soil under plane strain condition is investigated in this study. A novel modal analysis is derived based on the assumption of vanishing vertical displacements of the soil-wall system. The horizontal displacements of the soil-wall system are expressed by a series of modes in terms of the separate variable method. The boundary value problem is solved by considering the soil-wall interaction. Good agreement of the proposed solution results with those by the available methods confirms its accuracy. Closed-form solutions are derived for the following: (i) the displacement and stress field of the soil-wall system; (ii) the stiffness in the *m*th mode and dynamic Winkler modulus of the soil; (iii) translational and rotational response factors of the wall; (iv) the displacement amplification factor at the wall top. Kinematic response of the soil-wall system is evaluated in order to assess dynamic behavior of the wall.

Keywords: Flexible cantilever retaining wall; Kinematic response; Soil-wall interaction; Modal analysis; Winkler modulus

1. Introduction

Retaining walls are usually used to support the pressures by the retained backfill. Site investigation indicated that the retaining structures may destroy during earthquakes (Fang et al., 2003). Despite the multitude of studies over the past decades, dynamic behavior of retaining wall is far from being well investigated. It is widely understood that the seismic excitation transmitted to the wall from the soil is different from the free-field motion because of the dynamic interaction between the wall and the retained soil. Generally, the soil to seismic loadings pushes the wall and, in turn, the wall may resist the deformation of the retained soil and react to the surrounding soil. Theoretically, the interaction is referred to as kinematic response of the soil-wall system.

The most commonly adopted method for dynamic response of retaining walls is the limit equilibrium (Mononobe and Matsuo, 1929; Okabe, 1924; Seed and Whitman, 1970; Richards and Elms, 1979; Nadim and Whitman, 1983; Sherif and Fang, 1984; Mylonakis et al., 2007; Azada et al., 2008; Ghosh, 2010; Di Santolo and Evangelista, 2011). In the limit state analysis, failure appears in a wedge of soil behind the wall under a pseudostatic load. Thus, intensive earthquake is the premise to ensure the retained soil achieves a limit state. This method has been widely used and adopted in many design codes in practice for its simplicity. However, the soil-wall interaction and dynamic behavior of seismic wave propagation are neglected in the limit equilibrium method. For full soil-wall interaction analysis, coupling of deformations of the soil and wall should be considered globally. Apart from some numerical solutions (Psarropoulos et al., 2005; Ling et al., 2005; Callisto and Soccodato, 2010), the analytical methods have been highlighted for the closed-form property, such as the early representative solutions (Matsuo and Ohara, 1960;

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Nomenclature

A	displacement ratio
A_g	acceleration amplitude
B_m	coefficient
$C_{1\sim4}$	solution function constants
d_w	nondimensional flexural flexibility
d_θ	nondimensional rotational flexibility
D_w	wall flexural rigidity
E_s, E_s^*	soil Young's modulus
E_w	wall Young's modulus
E_{s1}	modified soil Young's modulus
$f_{1\sim4,p}$	solution functions
$F_{1m\sim4m}$	constants
G_s, G_s^*	soil shear modulus
H	soil thickness
I_u	translational kinematic response factor
I_w	inertia moment of wall
I_ϕ	rotational kinematic response factor
k	equivalent soil spring stiffness
k_m^*	complex valued stiffness of soil
$\bar{k}_m^*$	complex valued stiffness of soil
m_w	wall mass per unit
M_w	bending moment of wall
$\{M\}$	matrix
Q_w	wall shear force
R_θ	rotational rigidity
t	time
t_w	wall thickness
T_m	parameter
u_{g0}	displacement amplitude of rock base
u_w	horizontal displacement of wall
u_x	soil horizontal displacement
u_y	soil vertical displacement
u^r	relative displacement of soil
u_w^{st}	static wall displacement
$U(x,\omega)$	function
$U_h(y)$	function to y
v_s	shear wave velocity of soil
$\{V\}$	matrix
α	parameter
β_0	damping ratio of soil
γ	parameter
η	soil parameter
λ	parameter for wall
λ_s, λ_s^*	lame constants of soil
λ_θ	parameter
$\nu_{w,s}$	wall and soil Poisson's ratio
$\rho_{w,s}$	wall and soil densities
$\sigma_x, \sigma_{xy}, \sigma_y$	stresses
σ_w	wall pressure
τ_m	parameter
ϕ	displacement attenuation function
φ	function to x
ω	cyclic frequency
Ω_m	parameter

Wood, 1973, 1975; Arias et al., 1981; Scott, 1973). It has been shown that Veletsos and Younan (1994a, 1994b, 1997); Younan and Veletsos (2000) made use of Lagrange's equations of motion and presented a series of complete accurate elastic models for dynamic responses of the rigid and flexible walls by vanishing vertical stresses of the soil-wall system. Wu and Finn (1999) presented a plane strain elastic solution for the problem by neglecting vertical displacements. Recently, the models of Veletsos and Younan (1994a, 1994b, 1997); Younan and Veletsos (2000) have been extended to the cases of different constrained conditions of the wall (Jung et al., 2010) and the poroelastic medium (Theodorakopoulos et al., 2001a, 2001b; Theodorakopoulos, 2003; Theodorakopoulos and Beskos, 2003; Lanzoni et al., 2007). The direct analytical solutions by Veletsos and Younan (1994a, 1994b, 1997); Younan and Veletsos (2000) are powerful and useful, but they are a little complicated (Theodorakopoulos et al., 2001b). The author proposed an analytical solution based on a modified Vlasov–Leontiev foundation model by vanishing vertical displacements with an iterative procedure (Liu et al., 2014).

The aim of this study is to present a novel analytical method for dynamic response of flexible cantilever retaining wall by the horizontal excitations in terms of modal analysis. The proposed model is similar to the continuum elastodynamic solutions to dynamics analysis for piles by Nogami and Novak (1976) and Tajimi (1969). In the present method, vertical displacements are neglected and only motions in the horizontal direction are taken into consideration. It will be shown that the present solution results are in good agreement with those by Veletsos and Younan (1997), even though their methodologies are quite different. Kinematic response of the soil-wall system and dynamic Winkler modulus of the soil layer will be investigated by the present method. In this study, the vibration of the soil medium is firstly analyzed to deduce its lateral resistance to the wall. Then, soil-wall interaction is taken into consideration to examine the dynamic response of the wall. The proposed solution is not only analytical and conceptual simplicity on the basis of conventional elastodynamics, but also has many distinct advantages and novelties over the analytical solutions available. The present model maintains the stress continuity of the soil-wall system in the vertical direction. Moreover, the modal shapes of the vibration of the soil and wall are determined according to the constraint conditions along the boundaries directly and free of empirical constants.

2. Model development

A soil-wall system subjected to transverse seismic excitations is considered as shown in Fig. 1. The soil-wall system is overlying on a rigid rock base with depth H from the soil surface. The wall is installed of length H, thickness t_w, Young's