Soil Dynamics and Earthquake Engineering 31 (2011) 879–890

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

1D harmonic response of layered inhomogeneous soil: Analytical investigation

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ARTICLE INFO

Article history:
Received 6 September 2010
Received in revised form
23 December 2010
Accepted 9 January 2011
Available online 8 March 2011

ABSTRACT

The seismic response of inhomogeneous soil deposits is explored analytically by means of one-dimensional viscoelastic wave propagation theory. The problem under investigation comprises of a continuously inhomogeneous stratum over a homogeneous layer of higher stiffness, with the excitation defined in terms of vertically propagating harmonic S waves imposed at the base of the system. A generalized parabolic function is employed to describe the variable shear wave propagation velocity in the inhomogeneous layer. The problem is treated analytically leading to an exact solution of the Bessel type for the natural frequencies, mode shapes and base-to-surface response transfer function. The model is validated using available theoretical solutions and finite-element analyses. Results are presented in the form of normalized graphs demonstrating the effect of salient model parameters such as layer thickness, impedance contrast between surface and base layer, rate of inhomogeneity and hysteretic damping ratio. Equivalent homogeneous soil approximations are examined. The effect of vanishing shear wave propagation velocity near soil surface on shear strains and displacements is explored by asymptotic analyses.

1. Introduction

Under certain conditions such as those encountered in thick and soft soil deposits, conventional analysis procedures based on discretizing the soil in a multi-layer system with constant properties within each layer, may underestimate soil amplification with respect to the actual response of a continuously inhomogeneous medium, depending primarily on frequency content of input motion. Based on a detailed in-situ investigation of dynamic properties of soft deposits, Towhata [1] demonstrated analytically that shear wave propagation velocity may vary continuously with depth even for complex stratifications involving different soil materials and geologic environments. In this case, pertinent analytical solutions reveal the possibility of higher amounts of seismic energy reaching the ground surface with respect to soils with discontinuous variation in shear modulus.

Along these lines, various research efforts on earthquake response of continuously inhomogeneous soils under vertically propagating shear waves have resulted in closed-form solutions for natural frequencies, mode shapes and base-to-surface amplification functions. Following the early work of Ambraseys [2] and Seed and Idriss [3], Dobry et al. [4] studied the dynamic response of inhomogeneous soils with shear wave propagation velocity of the form $V_s = cz^n$, z being depth and n a positive inhomogeneity coefficient associated with zero shear modulus at ground surface. A special case of the above equation, corresponding to $n=2/3$, was adopted by Travasarou and Gazetas [5] as part of an investigation of seismic response of soft marine clay sediments. Based on earlier suggestions by Dobry et al. [4] and Towhata [1], the above authors showed analytically that seismic strains may tend to infinity at soil surface, depending on the rate of increase of shear wave velocity with depth. Heterogeneous soils with shear wave velocity increasing from a non-zero value at the free surface were examined by Ambraseys [2], Toki and Cherri [6], Schreyer [7] and Gazetas [8], focusing on the effect of rate and type of heterogeneity. An extended one-dimensional model was later developed by Towhata [1], who investigated the behavior of the medium for the whole set of positive inhomogeneity coefficients ($0 < n < \infty$), considering zero or finite stiffness at the surface. More recently, Parashakis [9] and Semblat and Pecker [10] presented analytical solutions of the wave equation for a heterogeneous soil profile with shear wave velocity increasing with depth according to a generalized power law (see also Ref. [33]) and different boundary conditions at the base. These solutions are extensions of those in the aforementioned references.

The effect of soil inhomogeneity has also been studied for different types of seismic waves in multiple dimensions. For instance, the late Professor Vardoulakis [11] considered the case of torsional

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0267-7261/$ - see front matter
doi:10.1016/j.soildyn.2011.01.007