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Pseudospectral modeling and dispersion analysis of Rayleigh waves in viscoelastic media

Kai Zhang [a], Yinhe Luo [a,*], Jianghai Xia [b], Chao Chen [a]

[a] Institute of Geophysics and Geomatics, China University of Geosciences, Wuhan, Hubei 430074, China
[b] Kansas Geological Survey, The University of Kansas, 1930 Constant Avenue, Lawrence, KS 66047-3724, USA

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ABSTRACT

Multichannel Analysis of Surface Waves (MASW) is one of the most widely used techniques in environmental and engineering geophysics to determine shear-wave velocities and dynamic properties, which is based on the elastic layered system theory. Wave propagation in the Earth, however, has been recognized as viscoelastic and the propagation of Rayleigh waves presents substantial differences in viscoelastic media as compared with elastic media. Therefore, it is necessary to carry out numerical simulation and dispersion analysis of Rayleigh waves in viscoelastic media to better understand Rayleigh-wave behaviors in the real world. We apply a pseudospectral method to the calculation of the spatial derivatives using a Chebyshev difference operator in the vertical direction and a Fourier difference operator in the horizontal direction based on the velocity–stress elastodynamic equations and relations of linear viscoelastic solids. This approach stretches the spatial discrete grid to have a minimum grid size near the free surface so that high accuracy and resolution are achieved at the free surface, which allows an effective incorporation of the free surface boundary conditions since the Chebyshev method is nonperiodic. We first use an elastic homogeneous half-space model to demonstrate the accuracy of the pseudospectral method comparing with the analytical solution, and verify the correctness of the numerical modeling results for a viscoelastic half-space comparing the phase velocities of Rayleigh wave between the theoretical values and the dispersive image generated by high-resolution linear Radon transform. We then simulate three types of two-layer models to analyze dispersive-energy characteristics for near-surface applications. Results demonstrate that the phase velocity of Rayleigh waves in viscoelastic media is relatively higher than in elastic media and the fundamental mode increases by 10–16% when the frequency is above 10 Hz due to the velocity dispersion of P and S waves.

1. Introduction

Rayleigh waves are valuable signals in several fields, from earthquake seismology and near-surface geophysical investigation to materials science. Recently, the Multichannel Analysis of Surface Wave (MASW) method has been widely used as a useful tool for determining the measurement of shear (S)-wave velocity and dynamic properties, which can be traced back to the early work by Song et al. [1]. This method, which utilizes a multichannel recording system to estimate near-surface S-wave velocity from high-frequency Rayleigh waves [2], is based on the elastic layered system theory [3].

Wave propagation in the Earth, however, has been recognized as viscoelastic. The effects of viscoelasticity on seismic waves are twofold [4]: (1) amplitude attenuation—amplitudes decay with propagation distance due to energy loss and (2) velocity dispersion—velocities vary with frequency due to the relaxation of stress and strain. Several authors giving a complete analysis [5–8] dedicated efforts to the study of viscoelastic Rayleigh waves. They showed that there are two modes of waves for viscoelastic Rayleigh waves. One corresponds to the usual elastic surface wave, and the other only exists in viscoelastic media for certain combinations of the complex Lame parameters and for a given range of frequencies. Moreover, the Rayleigh wave energy velocity may be greater than the body-wave velocities. Carcione [9] investigated the Rayleigh-wave characteristics from the standpoint of energy by considering a general viscoelastic medium. He pointed out that the viscoelastic properties calculated from energy considerations are consistent with those obtained from the Rayleigh secular equation, and the energy velocity is not equal to the phase velocity.

The purpose of this work is to study the dispersion of Rayleigh waves in viscoelastic media. A pseudospectral modeling method is proved to possess high accuracy [10] for Rayleigh-wave modeling in viscoelastic media, which calculates the spatial

* Corresponding author. Tel.: +86 15071243298.
E-mail addresses: luoyinhe@gmail.com, luoyinhe@cug.edu.cn (Y. Luo).

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