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Finite-difference time-domain method for modelling of seismic wave propagation in viscoelastic media

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ABSTRACT

A finite difference formulation for the equations of SH waves in viscoelastic media has been developed and applied to the problem of an infinite half space with a buried source emitting a compressional pulse. A dispersion relation has been developed by employing the finite difference (FD) method, which has been used to discuss the stability criteria and also for obtaining the relation for phase and group velocities in viscoelastic media. Furthermore, the effect of variation of stability parameter on phase and group velocities; effect on the wave propagation with increase in dispersion parameter; and change in the wave propagation at different locations from the source have also been studied. The SH waves are found to be dispersive in viscoelastic media. The phase velocity increases with decrease in stability parameter. Furthermore, the location of the source has an important effect on the strength of the wave propagation in that the intensity of wave and therefore its longevity is inversely proportional to the distance from the source, implying that the wave will progressively die out exponentially.

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1. Introduction

As is well known, the Earth's interior consists of solids, liquids and trapped gases, the solids being called minerals. The minerals, found in many crystalline forms (e.g. isometric, trigonal, tetragonal, hexagonal, orthorhombic, monoclinic, and triclinic), are elastic bodies, bound by natural plane surfaces or faces. Concurrent with this, viscoelastic solids are also found in the Earth's interior. As the tectonic plates move and collide with one another, tectonic eartquakes occurs, and seismic waves are produced. During the earthquakes, two main types of seismic waves, namely body waves and surface waves are generated. While the former travels through the Earth's inner layers, the latter moves usually through the Earth's crust only. The surface waves are mostly responsible for the damage and destruction associated with earthquakes, during which the surface waves propagate through the afore-mentioned solids, which serve as the media of propagation for the seismic waves. Furthermore, during the seismic wave propagation, not only are the structural changes are produced in the mineral constituents of the rocks through which they propagate, but the magnitude of the wave propagation and hence the intensity of the earthquake itself, is also affected as the medium of propagation changes. It is to be borne in mind that for simulations of seismic wave propagation, *seismic wave amplification* and *seismic site effects* are considered the key factors in the earthquake engineering [2,4,5,13] as because the local amplification of the seismic motion is usually very large. The phenomena of wave

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amplification and site effects have serious implications in that they are prone to fortify the incident seismic motion and, in turn, depending upon their magnitude largely increase the devastating consequences on buildings and structures.

Although various mathematical models have been developed by simulating the wave propagation in the Earth's complex geological structure, employing different techniques such as finite differences, finite elements, spectral methods or boundary elements as also the hybrid methods [2,3,9,17,25,32], they have been constantly improved to obtain accurate and reliable solution of the wave equation for various media. Still, the finite-difference method, because of its power and flexibility to model wave propagation accurately in practically all the media of the Earth's complex interior and despite its limitation of failing in complex topography, continues to be an efficient and reliable method [23,24], and thus has gained a distinct edge over other methods of modelling. The superiority of this modelling technique is further accentuated by its unique characteristics, viz., its power, accuracy, rapidity and flexibility. Furthermore, where other schemes for solving the wave equation involve some sort of approximation, the finite-difference method also provides approximate, not exact, solutions for the partial differential equations problems. Finite difference technique has the potential and ability to provide much improved and accurate predictions of the displacement of the wave propagation throughout the medium, even for such situations also where the fundamental equations are well known but analytical solutions at all the points of the medium are not possible.

Because of this versatile feature, the finite-difference method is now finding large applications in earthquake ground motion modelling and also in the analysis of seismic wave propagation in complex structures of solid Earth, including large velocity contrasts, strong heterogeneity, topographic relief, and attenuation.

While modelling SH wave propagation, it must also be borne in mind that the wave motion in real media varies considerably from the one in ideal elastic solid, the latter situation being rare. Owing to several factors like geometrical spreading, reflections at the boundaries and an additional loss, i.e. attenuation, the amplitude of the seismic waves diminishes as the waves propagate through the Earth. Additionally, wave attenuation and dispersion considerably affect the amplitude and travel time of the wave field. Despite many attenuation mechanisms mentioned so far, not a single one takes into account the seismic attenuation applicable to all situations. It may also be mentioned in this context that the analysis of attenuation process is limited to linear range, that is weak earthquakes, though several attempts have been made to investigate the nonlinear models also [10,11,22]. Notwithstanding this, one approach to introduce attenuation into the wave equation considers that stresses are directly proportional to time derivative of the strain. The model based on this approach is applicable to imperfectly elastic bodies, including viscoelastic bodies, which, defined simply, are bodies or media with properties intermediate between those of elastic and viscous bodies.

Several attempts have been made in recent years to model the seismic wave propagation in viscoelastic media [7,12,26,30]. These studies have taken into consideration different parameters of viscoelastic media for developing the SH wave propagation models. Combining the pseudo excitation method (PEM) with precise integration method (PIM), Gao et al. [15,16] developed a very efficient and accurate solution method for modelling the propagation of stationary random waves in a viscoelastic, transversely isotropic and stratified half space. It was shown by these authors that the surface waves are very important for the wave propagation problem. Further, by comparing the analytical solutions with the numerical results, these authors demonstrated that the developed algorithm has extremely high precision. In another study, Kaur et al. [21] calculated the reflection and transmission coefficients due to incident plane SH-waves at a corrugated interface between two isotropic, laterally and vertically heterogeneous viscoelastic half spaces. Through these studies, they computed the variations of reflection and transmission coefficients for the first order of approximation of the corrugation vs. angle of incidence, corrugation and angle between propagation and attenuation vectors. A comparison of the coefficients in both the viscoelastic and uniform elastic media was also made, whereby they concluded that the values of the coefficients in viscoelastic media are larger than those in case of elastic media. In a related work, Chaudhary et al. [8] studied the problem of reflection and transmission of plane SH waves through a perfectly conducting self-reinforced elastic layer interposed between two vertically inhomogeneous (i.e. heterogeneous) viscoelastic solid half spaces, which was taken as exponentially varying along vertical direction. Ivanov and Savova [18,19], while studying the mechanical characteristics and structure of surface waves of an assigned wavelength as well as their propagation and comparing them with the corresponding characteristics of the rotational body waves in viscoelastic medium and Rayleigh waves, showed that there exists only one viscoelastic surface wave of an assigned wavelength, which satisfies the criteria for behaviour at infinity. In yet another study on viscoelastic finite difference modelling of SH waves, Robertson et al. [31] showed that the real earth media disperse and attenuate the propagation of mechanical waves, thus exhibiting anelastic behaviour, which was well explained by their model. It was concluded that a staggered scheme of second order accuracy in time and fourth order accuracy in space is optimally efficient. In an excellent and exhaustive state-of-the-art article Moczo et al. [28] have critically reviewed the recent developments in finite difference time domain modelling of seismic wave propagation and earthquake motion, addressing such important topics as material discontinuities, realistic attenuation, anisotropy, the planer free surface boundary condition, free surface topography, wave field excitation, non-reflecting boundaries and memory optimisation and parallelization.

An analysis of the published literature indicates that although the finite-difference technique has been applied to model the seismic wave propagation through different media of earth's interior, only limited and scanty studies are available on the application of finite difference techniques in viscoelastic media of the Earth's interior taking into consideration the source term. Thus, there is still ample scope for developing more efficient models by incorporating the wave-generating source term in the formulation of the problem, upon which the seismic wave propagation is prone to depend to a very large extent. Such a model will obviously not only provide accurate and detailed predictions of the displacement of the wave propagation throughout the viscoelastic medium, but will also facilitate the understanding and interpretation of seismic characteristics

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