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Numerical analysis of Rayleigh wave propagation in viscoelastic layers in the presence of topography

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ABSTRACT

Rayleigh wave has been widely used to investigate the subsurface ground media due to its vulnerability to ground properties through which it propagates. Accurate interpretation of Rayleigh wave dispersion mechanism is essential to ensure reliable surface wave seismic surveys such as Multichannel Analysis of Surface Waves (MASW). As surface waves are superposition of P- and SV- waves trapped near the free surface, topography of the free surface plays significant role in determining the characteristics of Rayleigh waves. This study investigates the effect of surface topography on the dispersion, mode composition, and phase velocities of recorded traces. Through Staggered-Grid Finite Difference method incorporated with Generalized Linear Solid Viscoelastic Model was used. Synthetic models combine concave and convex segments with models with different number of viscoelastic soil layers, representing of typical Korean subsurface ground types. A 20 Hz vertical point load excites fundamental and higher Rayleigh modes, which are recorded by a dense receiver array. The results showed that topography highly affects the dispersion of Rayleigh waves, possibly misleading the conventional inversion scheme to expect spurious low velocity layer. Through integration of these datasets into the training of deep learning inversion schemes, dispersion inversion can integrate the effect of topography unlike conventional schemes, which assumes horizontal and homogeneous layers.

1. INTRODUCTION

Seismic methods plays a significant role in the era of geotechnical and environmental engineering as they offer noninvasive means to investigate underground properties, assess groundwater condition, and evaluate potential hazard. Among these,

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surface-wave techniques have long been utilized for their cost effectiveness and rapid employment. By analyzing the propagation of elastic waves along the Earth's surface, engineers can infer shear wave velocity profiles that is closely related to stiffness, layering, and attenuation characteristics of the subsurface.

Multichannel Analysis of Surface Waves (MASW) makes use of the dispersive nature of Rayleigh waves, surface confined waves resulting from coupled P- and SV-motions, to invert for layered velocity structure. In a MASW survey, a vertical source generates a broadband elastic wavefield and the change within its propagation through the medium is recorded by an array of receivers. Dispersion curves are then extracted and matched to theoretical models under the assumption of horizontal, flat and homogeneous layer properties. While MASW has proven effective in many settings, its reliance on simplified, planar free surface geometry can introduce systematic bias when real topography deviates from these assumptions.

Because Rayleigh waves are intrinsically bound to the free surface, their characteristics such as their mode composition, phase velocity, and energy partitioning are very vulnerable to any variations in terrain. This cannot be fully taken into account in the traditional dispersion analysis using analytical inversion schemes which require assumption of a flat layers. Ignoring these geometric influences risks misidentifying low-velocity layers or overestimating attenuation, with direct consequences for site-response predictions and seismic hazard models.

Therefore, we implement a two-dimensional staggered-grid finite-difference solver coupled with a Generalized Linear Solid viscoelastic model to simulate Rayleigh-wave propagation over convex and concave topography. By systematically varying slope amplitude and subsurface layering, our numerical experiments quantify how surface topography complicates dispersion curves and confounds conventional inversion. Ultimately, integrating these topographic effects into inversion frameworks will enhance the applicability of MASW techniques across complex terrains.

2. METHODS

2.1 Viscoelastic wave

MASW has been widely used for geophysical surveys, commonly based on elastic layered system theory. However, linear elasticity is incapable of describing energy dissipation that occurs at a very low strain level, which is commonly encountered in many seismology and geotechnical problems. At this range of shear levels, the response is inelastic due to energy dissipation although no stiffness reduction is observed. Linear viscoelasticity, on the other hand, is a simplified model for describing energy dissipation, providing more accurate description for wave motion through attenuative geomaterials. Linear viscoelasticity models this behavior by coupling elastic springs and viscous dashpots, allowing both energy storage and time-dependent dissipation. (Lai et al., 2002)

Modelling viscoelastic wave propagation was done by following finite-difference scheme to solve the first-order linear partial differential equations on a staggered grid presented by Robertsson et al. (1994). Free surface boundary condition along the surface topography was modeled by modeling vacuum formulation above ground and explicitly setting the stress at the free surface zero, reflecting the velocity field across surface node, cleaning out spurious energy in the vacuum region fields. (Zhou et al., 2023)

2.2 Numerical model

4 cases of numerical models were built based on typical Korean subsurface environments based on previous researches. As for the geology of Korea, most of the bedrock, except for some on the east coast, is composed of a bed rock with a shallow weathering depth and strong strength. The upper sediments are generally distributed in shallow depths within 20m, except for large fault zones and large rivers.

Cases were built by first setting different depth of soft bed rock, 10m for case A, 20m for case B and C, and 25m for case D. Layers above the bed rock were built by selecting different combinations of fill, alluvial soil, weathered residual soil, weather rock layers. Viscoelastic parameters, Vp, Vs, Density, Qp, Qs, were selected to represent the desired layer property. Ricker wavelet with 20Hz center frequency was injected to approximate sledgehammer impact, and long array of receivers were placed along the surface. As can be seen from Table 1, 24 different models were constructed to compare and analyze the effect of layer composition, surface shape and height.

Table 1. Case construction

Layer composition	A	B	C	D
Surface shape	Flat	Concave	Convex	
Height [m]	0.5	1.0		

3. RESULTS AND CONCLUSIONS

Data received from the receiver array was processed to obtain plots of frequency response, seismic shots, and dispersion images. By comparing the results in three different plots, the effect of layer composition, surface shape, and height was analyzed. Examples of seismic shots and dispersion images under different surface shape and height are shown in Fig. 1.

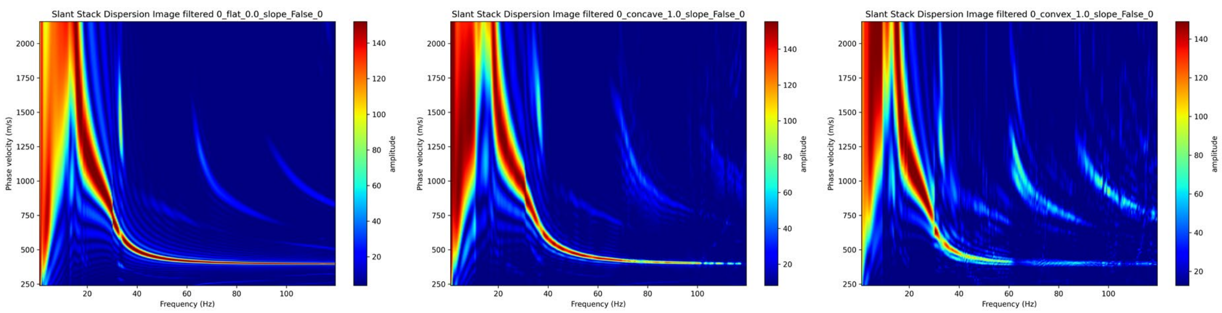

Fig 1. Comparison of dispersion image for different surface shapes

We investigated topographic effects by separating (1) the effect of surface geometry (flat, concave, convex) and (2) the effect of relief amplitude for the non-flat cases.

Rayleigh waves consist of coupled P and SV motions whose energy is trapped in a near-surface waveguide. When the free surface undulates, the effective waveguide thickness varies laterally and leads to changes in the dispersion characteristics. Concave surface locally deepens this waveguide, making it behave like a thicker, low velocity layers. As a result, wave energy concentrates in the trough, local amplitude increases, and the high frequency component of the fundamental phase velocity shifts to lower region. On the other hand, convex surfaces thins the near surface waveguide, promoting energy leaking into adjacent regions and enhancing modal decoherence. This scattering diminishes local amplitude and yields a slight increase in high frequency apparent phase velocity. Only a minor deviation of dispersion across all modes was observed with small height of undulation while noticeable perturbation, particularly at higher frequencies, were detected in forms of irregular branches in dispersion image for surface with bigger height of undulation.

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REFERENCES

Robertsson, J. O. (1996). A numerical free-surface condition for elastic/viscoelastic finite-difference modeling in the presence of topography. Geophysics, **61**(6), 1921-1934.

Zhou, Xuhui, et al. "Finite-difference method for modeling the surface wave propagation with surface topography in anisotropic-viscoelastic media." Journal of Applied Geophysics **217** (2023): 105161.

Lai, C.G., & Ris, G. J. (2002). Solution of the Rayleigh eigenproblem in viscoelastic media. Bulletin of the Seismological Society of America, **92**(6), 2297-2309.