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Modeling Rayleigh Waves Using Elastic Finite-Difference Simulations

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Abstract Summary

In this study, we investigate elastic simulation aimed at generating realistic onshore seismic data. The modeling is based on the stress-velocity formulation of the elastic wave equation, solved numerically using the finite-difference method on a standard staggered grid. We analyzed wavefields snapshots, vertical-component seismograms, f-k spectra, and phase velocity estimates for four scenarios representing typical onshore survey conditions. The results demonstrate that the inclusion of both air layer and a near-surface low-velocity (weathered) layer is essential for generating Rayleigh waves, the primary component of ground roll. The f-k analysis and phase velocity estimates reveals a highly dispersive surface wave in the registered data.

Introduction

Rayleigh waves, which constitute the primary component of ground roll, are a dominant feature in onshore seismic data, often regarded as noise due to their high amplitudes and dispersion. However, they also carry valuable information about near-surface properties, which is critical for static corrections, particularly weathering static correction, and shallow imaging.

Ground roll is particularly influenced by near-surface heterogeneities, such as low-velocity layers (Sánchez-Galvis et al., 2021). Accurately modeling these surface waves requires careful attention to wavefield components, boundary conditions, and source injection.

This work investigates how surface conditions and shallow structure affect Rayleigh waves using 2D elastic wave simulations based on the stress-velocity formulation. We compare free-surface and air-layer models, with and without a low-velocity layer, and analyze the resulting seismograms in both time and f–k domains.

Methodology

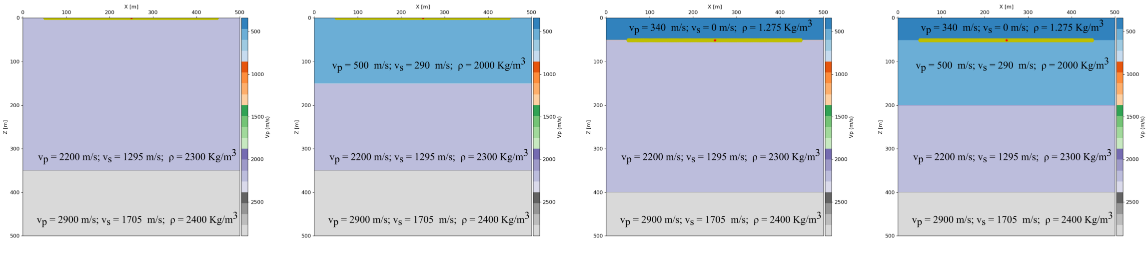
We simulate elastic wave propagation using the 2D elastic wave equation in the stress-velocity formulation (Virieux, 1986), discretized on a staggered grid via finite-difference time-domain (FDTD) methods. As a reference for modeling validation, in homogeneous media the Rayleigh wave phase velocity is approximately given by $v_r \approx 0.92 v_s$ (Jiang, 2012).

This formulation improves numerical stability and accuracy, particularly in the modeling of surface waves, due to the staggered sampling of the stress and velocity fields, permitting the simulation in fluid and solid media. The simulation uses a spatial grid spacing of 1 m, a time step of 0.1 ms, and Convolutional Perfectly Matched Layer (CPML) absorbing boundaries (Martin and Komatitsch, 2009) on all sides to mitigate artificial edge reflections.

The source is a Ricker wavelet with a cut-frequency of 60 Hz, injected in the vertical particle velocity component. The seismograms are extracted from the vertical velocity field, recorded slightly below the surface to avoid numerical artifacts and to better capture the Rayleigh wave motion.

To assess the influence of near-surface conditions on Rayleigh wave generation and ground roll behavior, we simulate elastic wave propagation in four 2D models, illustrated in Figure 1. Models in the Figure 1 (a) and (b) represent semi-infinite space with a free-surface boundary condition, where the vertical stress is zero at the surface (Levander, 1988). In contrast, Models in the Figures 1 (c) and (d) incorporate an explicit air layer above the solid domain, creating a physical interface that affects wave propagation at the surface.

Models in the Figure 1 (b) and (d) include a near-surface low-velocity layer, representing a weathered zone with reduced velocity. The thickness of the layers is designed to minimize internal multiples and reverberations within the recording window, enabling a clearer analysis of surface wave behavior



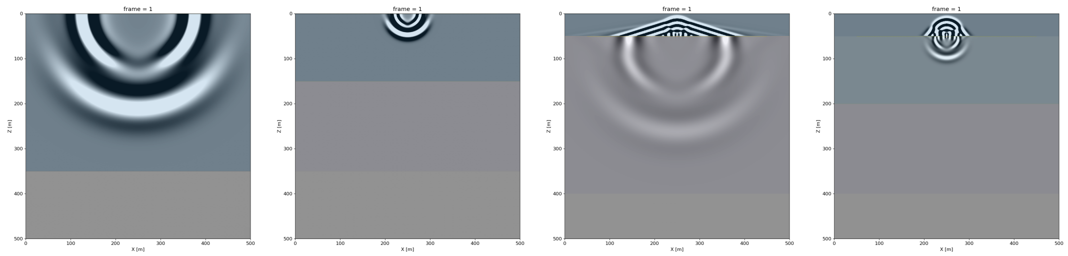
(a) (b) (c) (d)

Figure 1: The four tested scenarios. a) Free-surface modeling with high velocity sediment. b) Free Surface modeling with low-velocity layer c) Air layer over high velocity sediment d) Air layer with low-velocity layer.

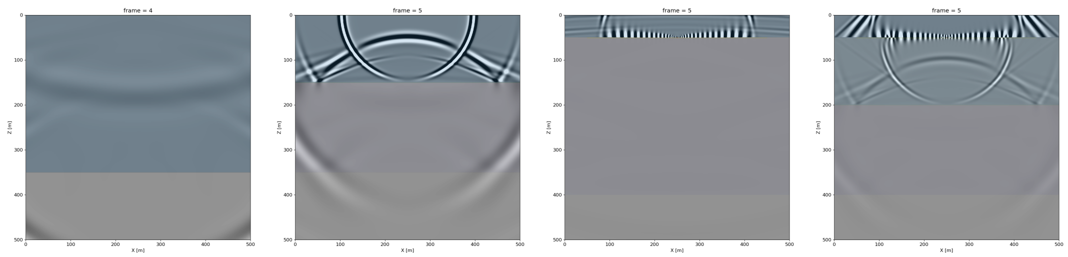
in seismograms and wavefield snapshots. Elastic parameters for each layer are annotated in the figure. These tests aim to compare how different surface representations, free-surface versus air layer, and the inclusion of a low-velocity zone affect the propagation of the surface waves.

Results

Snapshots of the vertical particle velocity wavefield for each scenario are shown in Figure 2. The top row (Figures 2 (a)-(d)) represents 0.1 s, and the bottom row (Figures 2 (e)-(h)) shows 0.5 s. In the high-velocity sediment model (Figures 2 (a) and (e)), P- and S-waves propagate rapidly, exiting the domain with minimal surface interaction.



(a) (b) (c) (d)



(e) (f) (g) (h)

Figure 2: Snapshots for each scenario at two propagation times: (a) and (e) free surface; (b) and (f) free surface with a low-velocity layer; (c) and (g) air layer model; (d) and (h) air layer model with a low-velocity layer. Top row: 0.1 s; bottom row: 0.5 s.

In the free-surface model with a near-surface low-velocity layer (Figures 2 (b) and (f)), more wave phenomena appear: direct P- and S-waves, PP and PS reflections, and mode conversions.

Yet, despite conditions favoring Rayleigh wave generation, no significant surface wave energy is observed, suggesting the free-surface alone is insufficient to generate Rayleigh waves under these parameters.

When an air layer is added above the sediment (Figures 2 (c) and (g)), a high-amplitude surface wave arises at the air-sediment interface, propagating more slowly than the air wave, indicative of a Rayleigh-type mode enabled by the physical boundary. A low-velocity air wave is also present. P- and S-waves still exit quickly due to the sediment's high velocity.

In the final model, combining an air layer and a low-velocity zone (Figures 2 (d) and (h)), the surface wave becomes even clearer and travels slightly slower than the S-wave. The Rayleigh wave is distinctly visible at the air-sediment interface, alongside direct and reflected body waves. The combination of air and weathered layers enhances surface wave visibility and realism.

Figure 3 presents vertical seismograms, f-k spectra, and estimated phase velocities for all scenarios. Phase velocity is computed as $v = \frac{\omega}{\kappa} = \frac{f}{k}$, with theoretical arrivals for v_p, v_s, and v_r overlaid. As expected, the vertical component is dominated by S-wave energy, with weak P-wave amplitudes.

In free-surface cases (Figures 3 (a) and (b)), Rayleigh waves are not prominent, and both the f-k spectra and phase velocities show dominant S-wave energy. Conversely, air-layer models (Figures 3 (c) and (d)) reveal clear, dispersive surface waves. The low-velocity layer further delays and slows the wave, consistent with Rayleigh behavior. The f-k spectra confirm coherent low-velocity energy, especially with the weathered layer. Dispersion curves from f-k maxima emphasize the strong dispersion caused by the low-velocity zone. These results show that both an air interface and a near-surface low-velocity layer are key to modeling realistic Rayleigh waves and ground roll.

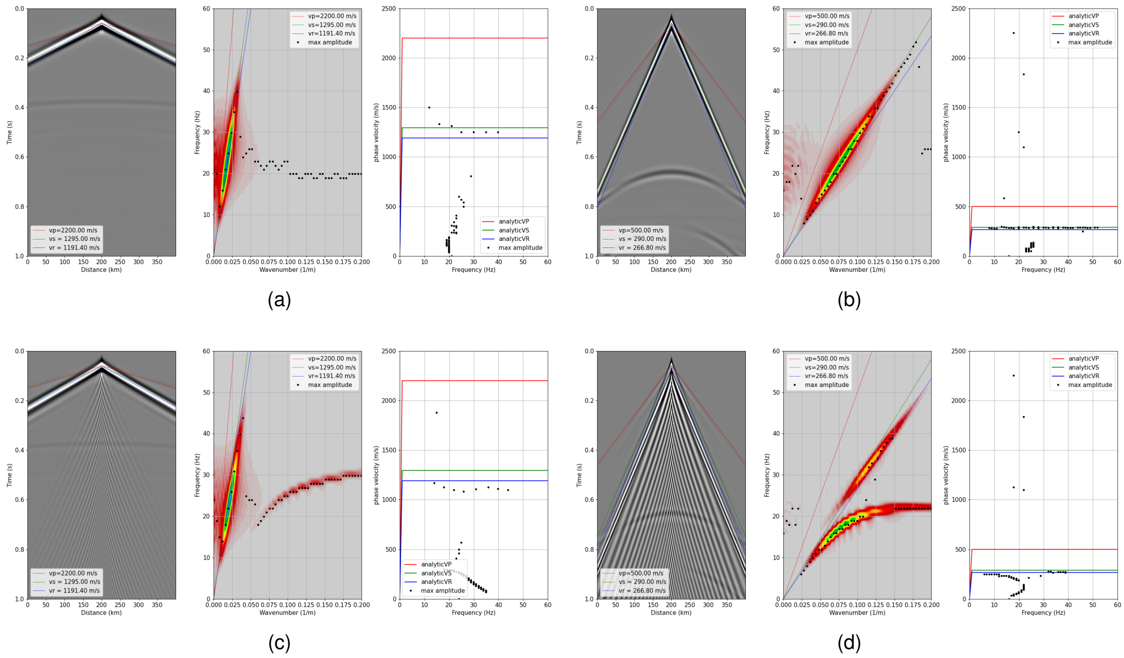


Figure 3: Vertical Seismogram, f-k spectra, and estimated phase velocity. a) Free Surface b) Free Surface with low-velocity layer c) Air layer model d) Air layer model with low-velocity layer.

Conclusion

This study investigated the generation and characterization of surface waves in elastic wave simulations under different near-surface configurations. Our results demonstrate that the inclusion of an air layer is essential for generating dispersive surface waves, while a near-surface low-velocity layer is critical for reproducing field-like Rayleigh wave dispersion and ground roll characteristics.

Based on these findings, we recommend several best practices for realistic ground roll modeling: (i) use the vertical component of particle velocity at the surface to enhance sensitivity to Rayleigh waves; (ii) adopt a stress-velocity formulation implemented on a staggered grid for numerical accuracy and stability; and (iii) ensure realistic near-surface material properties, particularly in the weathered zone, to properly capture dispersion effects.

Future work should explore the inversion of surface wave dispersion curves to estimate near-surface properties. Additionally, extending the modeling framework to viscoelastic and anisotropic media will allow more comprehensive simulations of realistic field conditions.

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