Ground roll as a tool to image near-surface anomaly

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Summary

On an uncorrelated field record obtained using a monotonic sweep, ground roll is displayed in increasing or decreasing order of frequency with each frequency well separated from all others. Phase velocity and attenuation characteristics of each frequency contain the average elastic property of near-surface materials down to approximately half the wavelength. An uncorrelated field record, therefore, by itself can be associated with a two-dimensional display of the change in near-surface elastic property. Through the redundancy in data acquisition and a simple data processing step, the uncorrelated field records can be transformed into a stacked section that can be correlated directly to the image of the change in elastic property of near-surface materials. This method can be effectively used to detect near-surface anomalies of various kinds.

Introduction

The penetration depth of ground roll changes with wavelength: the longer wavelength penetrates deeper (Figure 1). When the elastic property of near-surface materials changes with depth, ground roll then becomes dispersive: propagation velocity changes with frequency. The propagation velocity, normally called phase velocity, is determined mainly by the average elastic property of the medium within the penetration depth. Therefore, the dispersive character of ground roll can be utilized to investigate the change in elastic property of near-surface materials.

When a multi-channel recording method is employed, the elastic property of near-surface materials can be investigated not only horizontally, but vertically as well. In this case, the horizontal change in elastic properties will alter both the phase-velocity and attenuation characteristics of surface waves with penetration depths greater than or comparable to the depth of the elastic property change. These two types of change will be observed on a multi-channel record as changes in linear slope and amplitudes of recorded waves.

When a swept-source like Vibroseis is used, each frequency component of ground roll is recorded with an excellent separation from other components with little interference effect on uncorrelated field record (Park et al., 1996). Furthermore, when sweep changes in a monotonic manner (e.g., linearly) with time, the recording time can be correlated directly to a depth that represents the approximate depth of penetration. Therefore, both vertical and horizontal changes of near-surface elastic properties can be investigated through various kinds of data analysis.

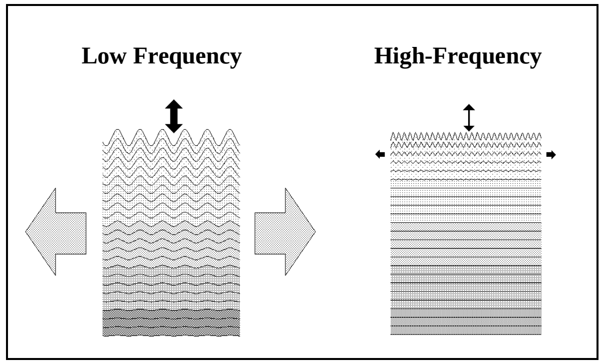

Figure 1. An illustration showing the penetration depth of ground roll changes with frequency and, therefore, different frequencies containing information of materials at different depths.

We present a simple technique that can lead to construction of a near-surface image representing a contrast in elastic property with respect to a reference location. A multiple number of shot gathers are collected over a certain surface distance in a fashion similar to the conventional roll-along mode for common-depth-point (CDP) surveys. The shot gathers obtained are then corrected for the offset effect by using a phase-velocity function analyzed from a shot gather at a reference location. All the traces in one shot gather are then stacked together to make one stacked trace. The stacked section consisting of all these stacked traces then shows an image of the change in elastic property of near-surface materials. This method is tested in the field by detecting a near-surface steam tunnel.

Surface-wave Response of Near-surface Anomaly

A near-surface anomaly is defined here as that part of near-surface materials that have elastic properties significantly different from the surrounding study area. The transition from normal zone to anomaly zone may be either abrupt or gradual.

During a ground-roll survey, the near-surface anomaly will leave a signature of its presence on multi-channel records in several forms. The most common of these would be different phase velocities for those frequencies propagating through or near the anomaly. Another form would be different attenuation characteristics.

Besides different phase velocities and attenuation characteristics, an anomaly may reveal its presence in the form of generation of higher modes (Båth, 1973; Gucunski and Woods, 1991), reflected and diffracted (Yanovskaya, 1989; Sheu et al., 1988) ground roll. Generation of the higher modes is closely related to existence of velocity inversion (Stokoe et al., 1994) and energy of the higher modes tends to become more significant for high frequencies (Tokimatsu et al., 1992). Reflected and diffracted ground roll will be generated if the transition from normal zone to anomaly zone is abrupt. All these types of anomaly signatures may appear on a multi-channel record when either the source or receivers are located at or near the surface location of the anomaly.

Theoretically, surface waves cannot penetrate a void filled with air or fluid because of the lack of shear modulus inside the void. However, the bulk of mass experiencing the retrograde elliptical motion of surface waves increases as penetration depth increases. Therefore, surface waves with penetration depths greater than or comparable to the depth of the void will experience certain changes in either attenuation or phase velocity, or both.

Field Procedure

Shot gathers are collected in a manner similar to the conventional roll-along mode for common-depth-point (CDP) surveys. The source-to-nearest-receiver offset is determined after considering the wavelength range of ground roll observed during walkaway tests (Park et al., 1996). Frequency range of sweep is determined by considering investigation depth range and the wavelength range together. Receiver spacing is determined by considering the horizontal dimension of the anomaly, phase velocities, number of channels in the seismograph, and the relative dominance of body-wave events. A swept-source like Vibroseis was used as source and field records were collected in uncorrelated format.

Data Processing Procedure

Dynamic linear move out (DLMO) correction is applied to each shot gather to correct for the offset effect, therefore, to flatten the linearly sloping events of ground roll (Park et al., 1996). The correction is a dynamic operation because the amount of correction changes with time as well as offset. DLMO can be accomplished in the frequency domain as follows:

$$W_{DLMO}(f,x) = e^{j\Phi_f} W(f,x),$$

where

$W(f,x)$ = Fourier transform applied to time axis of a shot gather, $w(t,x)$,
$W_{DLMO}(f,x)$ = Fourier transform of DLMO-corrected shot gather, $w_{DLMO}(t,x)$,
x = distance from source,
Φ_f = $2\pi fx / C_f$, and
C_f = phase velocity for frequency *f*.

The velocity function C_f used in DLMO correction is calculated from a shot gather obtained at a reference location. The reference location is a presumably normal zone within the survey line. All traces in a DLMO-corrected shot gather are then stacked together to produce one stacked trace per shot.

After stacking, this procedure achieves the following:

- Those frequencies that have the same phase velocity as that at the reference location will have large stacked amplitudes through constructive interference.
- For those shot gathers obtained at or near the surface location of an anomaly, DLMO correction will result in stacked traces of weak amplitudes through destructive interference for those frequencies that have penetration depths comparable to the depth of the anomaly.
- All the higher modes will be attenuated through destructive interference because of their different phase velocities.
- All nonplanar, reflected, and diffracted ground rolls (and possibly any body-wave events) will be attenuated through destructive interference because of their nonlinear occurrence on a multi-channel record.
- Random noise will be attenuated.

Ground roll imaging of near-surface anomaly

When stacked traces are displayed, all the normal zones will show large amplitudes and the anomalous zones will be denoted by attenuated amplitudes. The degree of attenuation will be proportional to the degree of being anomalous with respect to the reference location.

Field Test: Detection of Underground Steam Tunnel

An experiment to detect a near-surface steam tunnel as an anomaly was conducted as a feasibility check of the method previously outlined. A soccer field on the campus of the University of Kansas, Lawrence, Kansas, was chosen as a test site where an underground steam tunnel (1.2 m x 2.0 m.) crosses under the field at depth of 2.0 m (Figure 2).

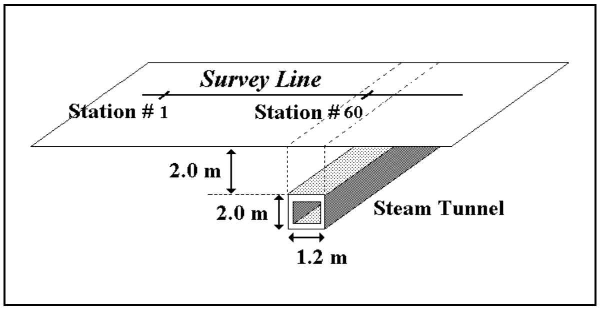

Figure 2. A diagram showing field geometry and location of steam tunnel.

Both shot and receiver intervals were 0.6 m, and 30 receiver groups of 10-Hz geophones were laid out. The source-to-first receiver was 16 m. A total of 70 shot gathers were collected. Acquisition started in such a way that the first several shot gathers could be collected with both source and receivers being kept well out of the surface location of the steam tunnel. An IVI Mini-Vib was used as source with 10 Hz - 150 Hz linear sweep and 10-s sweep time.

Dispersion curves were constructed from the first five shot gathers using a method by Park et al. (1998). An averaged phase-velocity function for the fundamental-mode ground roll was prepared from these curves. This velocity function was then used for the dynamic linear move out (DLMO) correction of all shot gathers obtained. Figure 3 shows an early portion of the stacked section of all these DLMO-corrected shot gathers. Depth scale is shown along with time scale. To display the depth scale in increasing order, the corresponding portion of the stacked data was flipped over and therefore time scale is displayed in decreasing order. The depth scale represents half the penetration depth (one wavelength). For this reason, any feature interpreted from the stacked section should be linked to the average elastic property at the corresponding depth at the reference location.

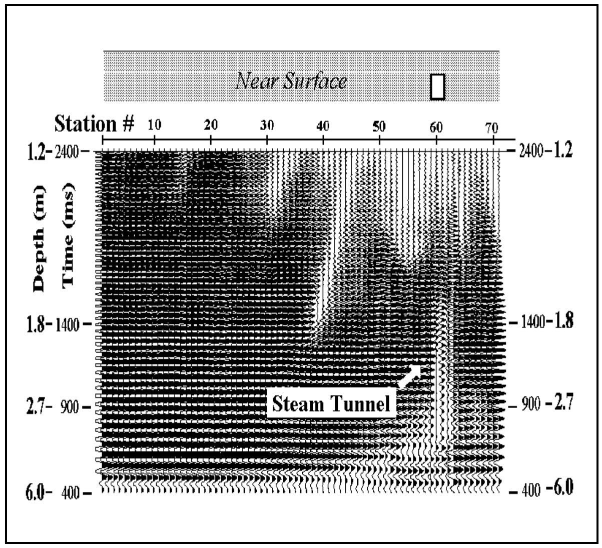

Figure 3. Stacked section of shot gathers collected during a field test after dynamic linear move out (DLMO) correction.

Existence of the tunnel is obvious on the stacked section as indicated by an approximately rectangular zone with weak amplitudes. Accuracy of the image is remarkable considering the generally accepted notion that the surface wave method is an average method. Along with the tunnel image, other anomalies at various other shallower parts are noticeable. These anomalies may be related to different moisture contents of the soil that affect the bulk density, or to different types of soil used during the construction of the tunnel and soccer field.

Discussion

This method of imaging with ground roll is one of the simplest form of seismic survey that can be implemented either as a separate survey or a byproduct of a body-wave survey. Despite its simplicity, the outcome can find invaluable usage in many applications. Examination of shot gathers indicates that those shot gathers collected with the source on top of the tunnel have much higher phase velocities with severe attenuation for those frequencies of ground roll that correspond to the image of the steam tunnel. This indicates the possibility of the generation of higher modes and therefore indicates that the existence of the tunnel may have played a similar role to the existence of a velocity inversion. The signature of ground roll seems to become more pronounced when the source, instead of receivers, is located on top of the anomaly as indicated by comparison of the shot-gather stack to the receiver-gather stack (Figure 4).

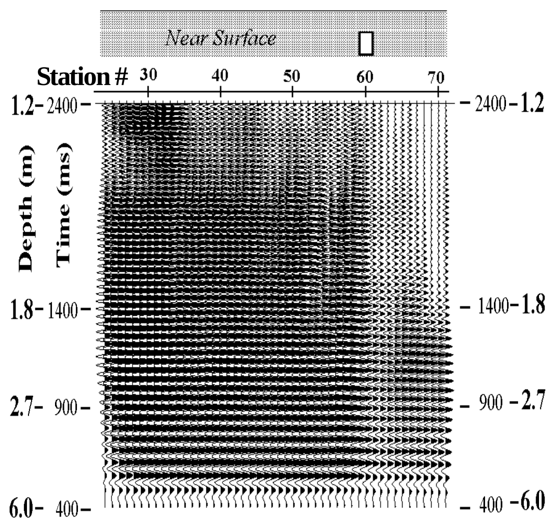

Figure 4. Stacked section of receiver gathers prepared from the same shot gathers that produced the stacked section shown in Figure 3.

It is possible to achieve similar result from shot gathers collected using impulsive sources like sledge hammer. In this case the equivalent uncorrelated shot gathers can be obtained through a simple convolution of the impulsive shot gathers with a synthetic pilot sweep. Field examples of using sledge hammer as the source will be discussed in a possible future publication.

Conclusions

Based on the well-known concept that ground roll travels horizontally along the near surface, with different frequencies mapping elastic property of materials at different depths, it is possible to image a near-surface anomaly through a simple form of data acquisition using a swept source and through a simple form of data processing without intensive analysis. The signature of a near-surface anomaly seems to become more pronounced on a multi-channel record when the source is located at the surface location of the anomaly than when receivers are located at the surface location of the anomaly.

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