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# Love waves: A menace to shallow shear wave reflection surveying

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## Summary

Shallow shear wave reflection profiling, in comparison to compressional wave surveys, requires a greater awareness of and ability to discriminate the many sources and associated forms coherent noise can take on shot gathers and the manifestation of that noise on CMP stacked sections. Shallow shear wave reflection surveying is an attractive alternative to compressional wave reflection surveys in some situations due in large part to the increased resolution potential at a given dominant reflection frequency, the polarized nature of the energy, insensitivity to pore materials, and the relationship of shear wave velocity to rigidity/stiffness of materials. Unlike compressional wave arrivals where reflections are the only coherent hyperbolic events, reflections and surface waves can appear hyperbolic on shear wave shot gathers. This unique difference should eliminate the complete confidence placed in unique interpretations of all hyperbolic events with a zero offset apex as reflections. Without careful attention to true measured velocities (ground truth) and complete removal of all energy arriving within the noise cone, Love waves will likely stack coherently on CMP sections. Interpretations made of stacked shear wave data which do not include sample shot gathers where reflection events are clearly identifiable outside the noise cone should not be considered legitimate and need to be assumed coherent noise.


## Introduction

Shear wave reflection is an extremely promising and alluring technique for imaging or characterizing the near surface in unique situations where the physical properties of shallow earth materials have constrained the effectiveness of compressional wave reflection surveying. This is particularly true where pore materials (gas) interfere with imaging deeper reflectors, or when estimating material characteristics, or if the frequency-to-velocity ratio at a site is higher for shear than compressional energy. The insensitivity of shear waves to pore materials is an especially beneficial property when trying to image beneath shallow gas (Pullan et al., 1998). As well, shear and compressional wave surveys collected along coincident profiles can provide reasonable estimates of Poisson's Ratio when reflections can be confidently correlated both between the two data sets and to specific reflectors (Miller et al., 2000). Since shear velocity is directly related to stiffness/rigidity, some engineering rock properties can be estimated from very detailed NMO velocity functions calculated during CMP processing of shear wave data. Considering the Vp/Vs ratios, resolution improvement for a given frequency seismic wave could be substantial on a shear wave stacked section from unconsolidated soils in comparison to an equivalent compressional wave survey (Hasbrouck, 1991). However, the very small optimum window (a small time and offset zone between the refractions and groundroll) plaguing most shallow shear wave reflection data, the difficulty producing and propagating broad bandwidth shear waves, and the daunting task of separating reflections from coherent noise, especially at near-offsets, represent formidable obstacles to the widespread use of shallow shear wave reflection imaging.

Theoretical resolution benefits of near-surface shear wave reflection in comparison to compressional wave reflection techniques are routinely touted as all the justification necessary for widespread application to any imaging task. The ratio of body wave dominant frequency to velocity (wavelength) is a measure of resolution potential. With the shear wave velocity of unconsolidated materials generally 3 to 4 times slower than compressional waves, seismic images produced using shear waves of comparable frequency to compressional waves could possess 3 to 4 times greater resolution. Unfortunately, it is generally difficult to produce, propagate, and record dominant shear wave reflection frequencies high enough, in comparison to compressional wave data, to take advantage of these lower shear wave velocities in most near-surface settings. In settings where the resolution benefits of shear waves make it possible to detect and/or delineate smaller targets than possible with compressional wave surveys, characteristic low signal-to-noise ratio and narrow bandwidth source wavelets generally inhibit actualizing these resolution benefits.

Practical realization of the benefits of shallow shear wave reflection profiling is rarely accomplished in most near-surface settings. It is common for the frequency content of the entire shear wavetrain to possess properties that would suggest improvement in resolution potential as suggested by theory. However, actualizing the theoretical potential of shear energy is only possible if true reflections are identified and separable from coherent noise on shot gathers. The ease coherent noise can be processed into coherent events and interpreted as reflections on shear wave CMP stacked reflection section makes this method extremely susceptible to misrepresentations of the subsurface. As will become evident later in this paper, if Love waves are not removed during processing they will stack quite nicely after NMO corrections and actually mask any true reflections that might be present in the early portions of the section. Velocity filtering actually enhances near-offset Love waves arriving within the noise cone (area defined by the first arrival of surface waves [Baker et al., 1998]). Hyperbolic arrival patterns cannot be used as the sole discriminating approach when separating near-offset reflections from Love waves. Unfortunately, many examples exist where coherent noise (Love waves), mode conversions, and narrow bandwidth body waves (refraction ring or guided wave) have unknowingly contributed to the production and interpretation of stacked noise as signal.

## Love waves in shallow shear wave reflection

The polarized nature of shear waves allow opportunities to enhance signal-to-noise ratios by forcing constructive interference of compressional waves. This unique characteristic of shear energy allows the first motion of the source wavelet to control the phase of the recorded energy. An example of how this characteristic could be used would involve the recording of two shots at the same location with the first source motion direction of the two records 180º apart. Then by reversing the recorded amplitude polarity of one shot record, the two records can be vertically stacked to reduce coherent compressional arrivals. Most signal enhancement approaches focusing on the polarity characteristics of shear energy rely on the destructive interference of compressional waves. Unfortunately, Love waves possess the same polarized characteristics shear bodywaves do and, therefore, phase reversals cannot be used to reduce the contribution of these surface waves.

Some soil types (e.g. certain clays and permafrost) seem to be particularly conducive to the production and propagation of more vertically travelling shear wave energy (Pullan et al., 1990; Miller et al., 1993). Loosely compacted dry soils appear to be fairly non-conducive to the production and propagation of shear bodywave energy, and are rarely capable of producing reflection frequencies within 25% of those possible with "equivalent" compressional wave methodologies. To avoid the inevitable pitfall of stacking coherent noise it is critical that significant supporting information (specifically borehole velocity measurements) about the seismic characteristics of the area studied be used to model and guide the entire acquisition, processing, and interpretation of shear wave data.

### Pitfall

One of the most common and troubling pitfalls shallow shear wave reflection surveys fall victim to is the stacking and interpreting of Love wave on CMP sections as body wave reflections. Love waves by their very nature travel within a layered earth. This travel path can produce surface wave arrivals with apparent hyperbolic curvature after the first arrival of the linearly propagating surface wave energy. Although surface wave arrivals in theory are linear and should possess no curvature, the apparent hyperbolic curvature often forms at near-offset traces due to the near-field effect of surface waves, the wave interference effect, or a combination of both (Park, 1999). These curved arrivals easily conform to what many consider the minimum characteristics for definitive interpretation as reflections. The curvature of these close offset groundroll arrivals is consistent with the shape of NMO velocity hyperbola and increase in apparent NMO velocity with time.

Interpreting shear wave reflections from within the noise cone should only be done in situations where the shear wave velocity structure is known (borehole measurement) and reflections of interest possess an NMO velocity at least 50% greater than the surface wave velocity. Since the shear wave velocity and surface wave velocity in the upper few meters are usually within about 10% of each other for unconsolidated materials, trying to separate reflections from surface wave arrivals using apparent NMO velocity only would not be advisable and practically speaking is virtually impossible. In geologic settings where the shear wave velocity changes very gradually with depth (i.e., loose, unconsolidated material) curved surface waves are a threat to realistic interpretations of reflectors within the first several hundred milliseconds.

As the surface waves travel farther from the source they become asymptotic to the linearly traveling first arriving surface wave energy. On shot gathers this phenomenon appears quite similar to the interaction between refractions and reflections at longer offsets (beyond wide angle). Hence, groundroll on shear wave data sets can appear both hyperbolic within the "noise cone" (after the first arrival of surface wave energy) and linear at longer offsets and where it is first recorded at a receiver. When a very low ratio of body wave to surface wave is observed, many times the surface wave can be mistaken for refractions and reflections. This is a unique characteristic of Love waves not seen in its compressional wave counterpart (Raleigh waves) and is therefore a problem that does not plague compressional wave surveys. The drive for success can many times overshadow the need for technical diligence and scientific rigor.

### Data Examples

Data presented in this paper demonstrate quite clearly how Love waves can manifest themselves as hyperbolic events perfectly fitting an NMO curve and arriving at a time later than the initial linear, dispersive groundroll event. At sites where the shear wave velocity changes gradually (thick unconsolidated overburden) with depth, the difference in velocity between the refracted shear and surface waves at equivalent offsets is small and therefore the high signal-to-noise ratio "optimum window" is quite small. Data used in this example are from a site with a 3 to 4 m thick, dry, low velocity unconsolidated layer on top of a thick sequence of sandstones and limestones. If the distinctive hyperbolic surface wave arrivals were interpreted as reflections, the apparent NMO velocities of around 200 m/s from layers as deep as 15 m would provide a very coherent CMP stacked section which would result in a completely bogus geologic interpretation at this site. Borehole data completely contradicts interpreting these curved groundroll arrivals as reflections. This same phenomenon will be observed in any data set with lower velocity (>1000 m/s) unconsolidated near-surface materials. Exacerbating this problem is the appearance of true shear wave reflections within 25% or so of the apparent NMO velocity observed in near-offset curved surface wave arrivals.

These data were recorded with single 14 Hz receivers were spaced 0.6 m apart and an IVI Minivib in SH configuration (Figure 1). A very dispersive ground roll arrival is the dominant event on the shot gathers. Shear wave refraction energy is obvious as the first arrival starting at offsets greater than around 3 m. A hint of coherent events arriving after the strong

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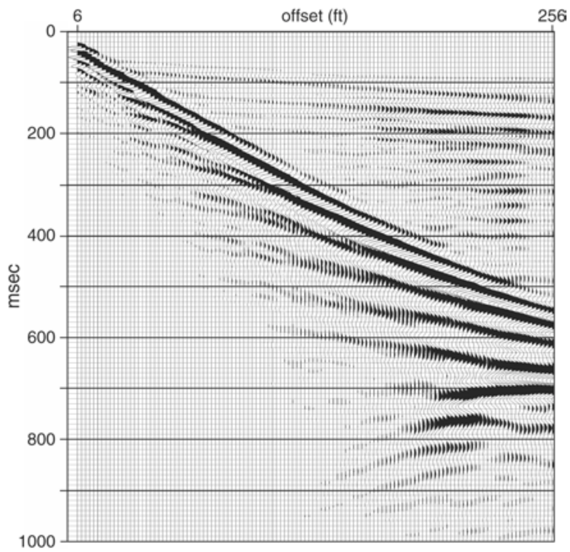


Figure 1. Raw shot gather after correlation. Strong surface wave arrivals are evident across the entire section.

linear first surface wave arrival are evident even on raw shot gathers.

As these data are run through a routine processing flow the entire wave train becomes evident when AGC is applied to the data (Figure 2). With the amplitudes balanced the distinctly higher velocity body wave arrivals appear before the arrival of the linear surface wave energy, while arriving after the surface wave are a series events with an apparent NMO-type curvature in the upper couple hundred milliseconds. These events have an apparent frequency higher than the surface waves arriving first and a unique curvature normally distinctive of reflections.

Velocity filtering is commonly used in CMP data processing to reduce the effects of linear arriving noise (usually surface waves or refractions). On some data, these linear arrivals are easily removed or at least suppressed using slope filtering techniques. After applying a simple f-k filter using a very conservative, narrow slice, focusing on the dominant linear surface wave arrival, the curved events immediately below the linear surface wave arrivals become pronounced. Based on their arrival pattern alone, they appear very reflection-like (Figure 3). Without a doubt these arrivals would move out and stack coherently on CMP stacked sections.

The arrival pattern of the curved events within the noise cone fit model hyperbolae almost perfectly (Figure 4). At this point, a less experienced or overzealous shallow reflection geophysicist might be fooled by these arrivals and proceed to produce and interpret stacked sections from these arrivals. Strong events would be interpretable at depths from as shallow as 50 ms to as deep as 500 ms. These arrivals would correlate in time to depths from about 3 to over 150 m. Although these velocities seem quite low, they are well within the range of values that have been observed in loosely compacted soils in borehole surveys. A key that should be noted by an experienced shallow reflection geophysicist is the significantly higher refraction velocity at offsets greater than about 3 m. This indicates that the apparent velocity properties

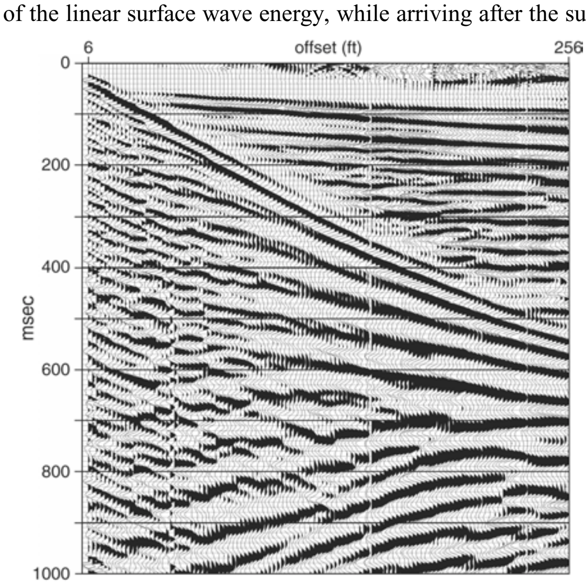


Figure 2. AGC (automatic gain control) applied to the raw vibroseis record. With all the coherent arrivals amplitude enhanced.

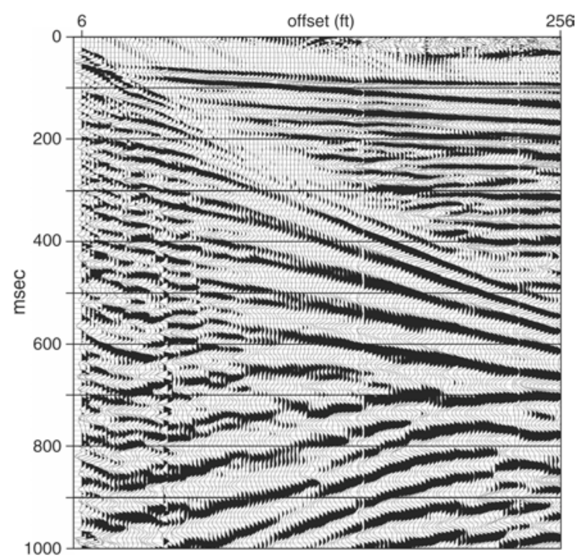


Figure 3. F-k filtering reduces or eliminates the linear arriving surface wave and enhances the curved arrivals within the noise cone.

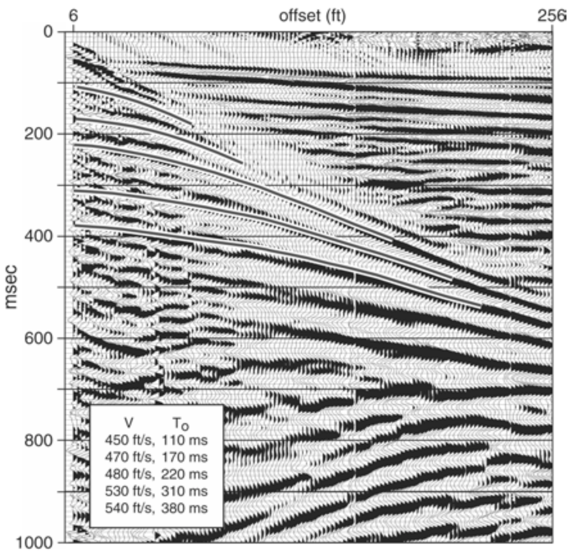


Figure 4. NMO velocity curves superimposed on the shot record.

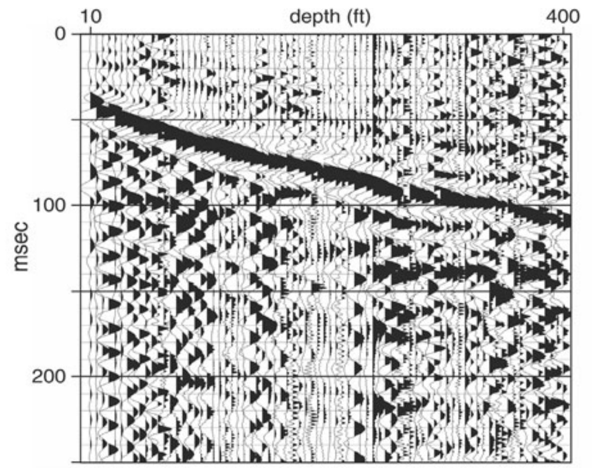


Figure 5. Shear wave down-hole survey. The high velocity bedrock at around 3 m depth is a clear indicator that the extremely low NMO velocities observed in arrivals within the noise cone are not realistic for this site.

of these data are not consistent. NMO curvature within the noise cone has been observed with apparent velocities as high as 500 m/sec on some shear wave shot gathers.

In other near-surface settings (e.g., more compacted near surface soils) these velocities will increase as the near-surface velocity (upper few meters) increases. Also, in situations where the high velocity bedrock present at this site is at significant depths, the refraction would be much slower and the key indicator used by the experienced geophysicist (discrepancy between refracted velocity and NMO velocity of the curved events) would not be obvious. Hence the pitfall and likely misinterpretation by even the experienced practitioner.

Looking at the downhole survey (check shot) for this location it is quite clear that the velocity below about 3 m increases from less than 100 m/s in the unconsolidated material to over 1500 m/s in the sandstone bedrock (Figure 5). The NMO velocity at time depths of over 100 ms should easily be in excess of 1000 m/s, an order of magnitude greater than observed on these data from curved events within the noise cone.

## Conclusions

Shear wave CMP stacked sections in areas where the velocity gradually changes with depth and the near surface generally consists of unconsolidated materials need shot gather verification highlighting events stacking coherently as truly reflections and not Love waves from within the noise cone possessing hyperbolic moveout. It is critical to incorporate good modeling and ground truth into any reflection survey, but it is especially important for shear wave surveys due to their tendency to produce curved coherent ground roll events that manifest themselves on CMP stacked sections (if proper inside muting is not undertaken). Coherent events on shear wave CMP stacked sections should only be considered legitimate if confident events observed after CMP stacking can be tracked to shot gathers and possess an NMO curve consistent with modeling, ground truth, and arrivals on traces outside the noise cone.

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