An examination of tube wave noise in vertical seismic profiling data

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ABSTRACT

Tube waves act as noise that camouflages upgoing and downgoing body wave events which are the fundamental seismic data measured in vertical seismic profiling (VSP). In two onshore vertical seismic profiles, the principal source of tube waves is shown to be surface ground roll that sweeps across the well head. Secondary tube wave sources revealed in these VSP data are the downhole geophone tool itself and the bottom of the borehole. Body wave signals are also shown to create tube waves when they arrive at significant impedance contrasts in the borehole such as changes in casing diameter.

Computer simulated vertical geophone arrays are used to reduce these tube waves, but such arrays attenuate and filter body wave events unless static time shifts are made so that the body wave signal occurs at the same two-way time at each geophone station. Consequently, actual downhole vertical geophone arrays are not an effective means by which tube waves can be eliminated. Power spectra comparisons of tube wave and compressional body wave events demonstrate that band-pass filters designed to eliminate tube waves also suppress body wave signals. A simple but effective field technique for reducing tube waves is shown to be proper source offset.

Using velocity filters to retrieve upgoing compressional events from VSP data heavily contaminated with tube wave noise yields in one example an agreement with surface measured reflections that is superior to that obtained from synthetic seismograms calculated from log data recorded in the same well.

INTRODUCTION

There are three basic modes of propagating seismic energy that can be observed in a borehole environment. Two of these modes are the compressional and shear body waves that propagate through the interior of the earth. In vertical seismic profiling (VSP), it is these body waves that one wishes to detect and analyze primarily because it is these energy modes that are recorded in surface seismic reflection profiles. The third type of seismic energy mode that can exist in a borehole environment is the tube wave, which is an interfacial wave traveling along the cylindrical fluid-solid boundary of the hole at a low, relatively fixed velocity and exhibiting no spherical divergence. Wave modes analogous to the tube wave for planar surfaces are the Rayleigh and Stoneley waves.

In some applications, the tube wave could be regarded as a useful seismic signal since it can be used to determine some physical properties of the earth surrounding the borehole (White, 1965). However, in VSP tube waves are probably best defined as noise because they camouflage the body wave events one really wants to see in VSP data. Therefore, all reasonable means should be taken to avoid tube wave contamination in VSP.

One way to avoid recording tube waves is to follow field procedures that prevent their generation. In order to do this, the mech-
anisms that create tube waves must be understood, and one purpose of this paper is to demonstrate some of these mechanisms. If changes in field procedures cannot eliminate tube waves, the only recourse is to structure the numerical data processing to eliminate them. Synthetic vertical geophone arrays and well designed velocity filters are two effective numerical processes that remove much tube wave noise from VSP data.

THE BOREHOLE ENVIRONMENT

It is essential to know the physical construction of a borehole in order to investigate tube wave behavior properly. The borehole diameter and rugosity, the type of casing, and the quality of the cement bond all affect tube wave character. The VSP data that are presented here were recorded in boreholes constructed in the manner shown in Figure 1. There is an interval of cemented double casing extending from the surface to a depth of 750 ft. The only other cemented portion of the wells is an interval of a little more than 2000 ft at the bottom of the holes. The remainder of the borehole consists of a single, uncemented 5 1/2 inch casing with a mud annulus between the casing and the formation. This borehole completion program is typical of many wells in critical seismic exploration areas.

It is important to verify whether or not meaningful VSP data can be recorded in boreholes of this type because it is logistically and economically better to record data in a cased onshore well than in an open hole where a drill rig is standing by. Borehole data have been published that establish there is no difference in the response recorded by a wall-locked geophone in an open hole and in a cemented cased hole (van Sandt and Levin, 1963). There is a noticeable absence of published data documenting the seismic response recorded in cased but uncemented boreholes.

EXAMPLES OF VSP DATA CONTAINING TUBE WAVES

One vertical seismic profile recorded in this type of borehole is shown in Figure 2. The same data are shown in Figure 3 with several energy modes interpreted. The principles by which primary reflections and multiples can be identified in vertical seismic profiles are described by Gal'perin (1974), Jolly (1953), and Levin and Lynn (1958).

These VSP data were recorded with a spatial sampling interval
(1) TUBE WAVE GENERATED AT BASE OF SURFACE CASING
(2) TUBE WAVE GENERATED AT SURFACE
(3) TUBE WAVE REVERBERATING BETWEEN TOOL AND SURFACE
(4) TUBE WAVE REFLECTED FROM BOTTOM OF HOLE

Fig. 3. Interpretation of principal energy modes observed in study well 1.

Fig. 4. Vertical seismic profile recorded in study well 1 with amplitudes adjusted to remove the effect of compressional wavefront divergence.
of 50 ft between geophone levels, and the energy source was two Y-600 Vibroseis® units. The vibrators were driven with a 13-sec upsweep starting at 8 Hz and ending at 64 Hz. A wall-locked device containing six vertically oriented 4.5 Hz geophones was used to record the seismic response. It has been reported that wall-locked geophones do not respond to tube waves in open or in cased, completely cemented boreholes (van Sandt and Levin, 1963). However, since tube wave events are observed in this experiment, it is obvious that wall-locked geophones do respond to tube waves in cased, partially cemented wells.

A numerical AGC has been applied to the data in Figures 2 and 3 to amplify low-amplitude events; consequently, the amplitudes of the tube waves should not be compared to the amplitudes of the body wave events. A more correct amplitude display of these same data is shown in Figure 4 where a \( V^2 T \) gain function has been applied to cancel the effect of spherical divergence on both the direct arrivals and the primary reflections. This amplitude reconstruction is based on the concept of a spherically spreading compressional event originating at the ground surface and traveling with rms velocity \( V(T) \) at recording time \( T \). The methodology employed is described by Morris (1979). The wavefront assumptions used in the method do not describe the behavior of the tube wave since the tube wave energy does not exhibit spherical divergence, and the observed tube wave events propagate at a fixed, relatively low velocity of about 4800 ft/sec rather than at the compressional wave velocity measured from first break times. Consequently, the reconstructed tube wave amplitudes in Figure 4 are too large, as are the amplitudes of the reverberating events in the shallow double cased interval. These reconstructed data do demonstrate the difficulty that is encountered when one tries to recreate “true amplitudes” in a vertical seismic profile that contains compressional, shear, and tube wave energy modes which exhibit different spherical divergence behaviors.

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**Fig. 5.** Model for downgoing tube wave mode 3. \( V \) is the tube wave velocity, \( Z \) is the depth of the geophone tool, and \( T \) is the tube wave arrival time.
When the data are presented in this type of amplitude display, it becomes obvious that anomalous waveforms are recorded in some depth intervals. The ringy, high-amplitude responses at 1600–1800, 2800–3000, and 4900–5100 ft are examples of these atypical data. Although not firmly established, these abnormal waveforms are assumed to be the result of loose casing.

Primary reflections can be seen in this vertical profile, but they cannot be followed all the way back to the ground surface. Each reflection can be traced upward until it encounters the zone containing the strong downgoing tube wave, and then further upward extrapolation of the event is impossible. Since one important use of vertical seismic profile data is to assist the interpretation of surface seismic profiles, the data will be more valuable if all upgoing events can be traced completely to grass roots to verify what surface geophones should record.

There are three downgoing tube wave events shown in these data. The source for these tube wave modes can be determined by following each event back to its point of origin. Upward extrapolation shows that the event labeled 1 is generated within the compressional direct arrival at a depth of 750 ft. This is the depth at which there is a change from double to single casing. Obviously, body waves can create tube waves at depth whenever they encounter a significant change in borehole impedance such as a change in effective borehole diameter. This fact is also documented by Ording and Redding (1953). The most dominant tube wave mode is the event labeled 2 in Figure 3. When that event is extrapolated upward, its origin is seen to be the ground surface itself. This is a significant observation because it leads to the conclusion that the basic cause for this mode existing in the borehole is the ground roll that sweeps across the well head from the seismic source. This knowledge tells us that any field procedure that reduces ground roll will also reduce this type of tube wave.

Tube wave modes 1 and 2 both tend to assume the character of the waveform that generated them. The basic Vibroseis wavelet is rather compact and essentially zero-phase and so is tube wave mode 1. The surface ground roll is a long, ringy, high-amplitude event, and so is tube wave mode 2.

Tube wave mode 3 is an interesting type of wave phenomenon, and the reason for this mode appearing in these data can be clarified by the illustration in Figure 5. This mode represents a tube wave that has made a single reverberation between the tool and the well head where the borehole terminates, and the tube wave reverberates between these two positions. At any depth the arrival time for the reverberated tube
wave would be three times larger than the arrival time for the direct downgoing tube wave, and that is exactly the effect seen in the VSP data. This energy mode could be mistaken for a primary downgoing event traveling with a velocity of 1600 ft/sec. The downhole geophone tool itself can thus act as a source for multiple tube wave generation. A design criterion for downhole geophone tools should be that they have as small a diameter as possible so that they create a minimum impedance contrast in a hole.

One other depth in this well, where there is a significant impedance change for propagating tube waves, is the termination of the borehole at 10,760 ft. Tube wave mode 4 marks the reflection of the downgoing tube wave from this change in borehole diameter. The VSP data could not be recorded below 9250 ft because a frac ring at that depth prohibited passage of the downhole tool. Linear extrapolation of modes 2 and 4 shows that mode 4 does originate at a depth of 10,760 ft. Thus, another source for tube wave generation in a well is the bottom termination point of the well. There is no evidence in these data that the compressional arrival creates a tube wave at the bottom of the borehole or at the top of the cemented interval (~8760 ft) as it did at the casing change at 750 ft.

EFFECTIVENESS OF DOWNHOLE ARRAYS

No wall-locked instrumentation exists in the Western Hemisphere that allows vertical geophone arrays to be implanted downhole. Current wall-locked VSP tools allow the seismic response to be measured at only one fixed depth point. Simultaneous recording of VSP data at several depth levels in a well is desirable for several reasons, the most important one being that the time now required to record data that are sampled correctly in the spatial domain is much too long. A secondary reason for having several geophone stations deployed simultaneously in a well is that a vertical array could be constructed that would reduce tube waves during the recording process. To evaluate this latter justification for developing VSP instrumentation capable of multiple depth level recording, vertical receiver arrays were created numerically in a computer by summing responses at adjacent geophone levels to create a single, composited trace that one would expect to be recorded by a linear vertical array of downhole geophones. This method of creating synthetic vertical arrays is described by Wunderschel (1976).

It is instructive to look at the frequency content of the tube wave events in order to make a judgment as to what type of synthetic downhole geophone array could be designed to effectively cancel them. Power spectra of downgoing compressional direct arrivals are compared with spectra of downgoing tube waves in Figure 6. The tube wave energy has essentially the same frequency bandwidth as does the compressional body wave energy. Consequently, simple band-pass filtering cannot eliminate tube wave noise without also strongly attenuating compressional events. The

![Diagram](image-url)

**Fig. 8.** Effect of synthetic vertical geophone arrays on the compressional wave signal in the depth interval 6800–7550 ft in study well 1. The time step-outs between the compressional arrivals are identical to those shown in Figure 2.
tube wave energy has a strong bimodal character, exhibiting both a dominating low-frequency and a dominating high-frequency component. The low-frequency tube wave peak at 18 Hz implies a wavelength of 267 ft, and the high-frequency peak at 55 Hz corresponds to a shorter wavelength of 87 ft. It is difficult to design a geophone array that will cancel energy that is this broadband and which has two dominant wavelengths that are so widely separated.

Some downhole tube wave responses that are generated by synthetic array modeling are shown in Figure 7. The time step-outs between the tube wave events entering into the summing process are identical to those shown in Figure 2. Array responses of time shifted data will be considered later. The experimental VSP data were recorded with a depth interval of 50 ft between geophone levels, thus if two adjacent downhole traces are summed, the response is that which would be recorded by an array of two geophones separated by 50 ft. If three consecutive traces are summed, the response represents an array of three geophones covering a vertical interval of 100 ft, etc. The tube waves attenuate as the array length increases; the maximum attenuation occurring for an array 250 ft long. The tube wave amplitude begins a gradual amplitude increase for arrays longer than 250 ft. These results support the premise that appropriately designed synthetic vertical geophone arrays can cancel much tube wave noise.

Even though vertical arrays reduce tube wave amplitudes, their overall benefit in vertical seismic profiling can be judged only after examining their effects on the compressional signal.

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FIG. 9. Effect of synthetic vertical geophone arrays on the frequency content of the compressional wave signal in the depth interval 6800–7550 ft in study well 1. The time step-outs between the compressional arrivals are identical to those shown in Figure 2.

FIG. 10. Effect of synthetic vertical geophone arrays on tube wave noise in the depth interval 6800–7550 ft in study well 1. The time step-outs between the tube wave events are adjusted so that the downgoing compressional events exhibit no time step-outs.
hose compressional data recorded by these same numerically simulated vertical geophone arrays are shown in Figure 8. Again, the time steps-out between the compressional arrivals being summed are identical to those shown in Figure 2. The arrays reduce the compressional signal amplitudes by essentially the same magnitude as they do the tube wave amplitudes. The arrays also attenuate the higher frequency components of the 8 to 64 Hz compressional sweep signal as shown by the power spectra calculations in Figure 9. An implication of this modeling exercise is that constructing actual downhole vertical arrays for the explicit purpose of reducing tube waves is inadvisable.

The filtering action on the compressional signal can be reduced if the traces are summed after they are first time shifted to align a given compressional event at the same recording time for all traces. The resulting VSP data are equivalent to a surface seismic measurement where vertically traveling compressional events impinge on a horizontal geophone array. The tube wave events in such time shifted VSP data would be analogous to nonvertical energy propagating across a horizontal surface geophone array. Vertical alignment of downgoing compressional events is accomplished by advancing each trace by an amount equal to its first break time. Upgoing events are vertically aligned by delaying each trace by an amount equal to its first break time. When the downhole data are time shifted so that the compressional first arrival occurs at time zero at all depths, the tube wave events have an apparent velocity of 8000 ft/sec rather than 4800 ft/sec as indicated by the original data in Figure 2.

The effect of synthetic vertical geophone arrays on tube wave cancellation after the downgoing compressional signal has been vertically time aligned is shown in Figure 10. Again, the tube wave amplitude reduces with increasing array length until the array reaches 350 ft, and then the tube wave amplitudes begin a slight increase. A longer array is needed to cancel the tube waves in this case because the time shifting has increased the apparent velocity of the tube waves and, therefore, increased the effective wavelengths of the tube wave events.

Since the compressional events are vertically aligned, the arrays exert no filtering action on the compressional signal other than averaging the compressional wavelets over vertical intervals of 50 ft, 100 ft, etc., and creating vertical uniformity of wave-shapes. This smoothing creates a higher signal-to-noise (S/N) character for the compressional data, but may destroy valuable individual compressional wavelet character that is essential in some detailed investigations of reflection-transmission properties, lithological analyses, and attenuation measurements. Unless individual compressional seismic wavelet character is needed at closely spaced depth intervals, summing time shifted traces by means of synthetic vertical arrays is an effective means of cancelling tube waves and other VSP noises.

**EFFECT OF SURFACE GROUND ROLL**

Since it may not be desirable in some VSP applications to cancel tube waves by synthetic vertical geophone arrays, another approach to tube wave control is to address the problem of how to reduce the ground roll that sweeps across the well head. An important factor in the VSP field geometry that must be considered is the effect of source offset. Shown in Figure 11 are downhole responses measured with the geophone secured at a depth of 3000 ft. The vertical dashed line marks the onset of the tube wave.

![Figure 11](image-url)
Fig. 12. Effect of source offset on tube wave generation when the geophone is at a depth of 5000 ft. The vertical dashed line marks the onset of the tube wave.

ft and with the vibrators stationed at offsets of 200, 400, and 685 ft from the well head. All of the recordings are normalized so that the first-break amplitudes are equal. At an offset of 400 ft, the two vibrators were also positioned in a two-element array designed to cancel the dominant wavelength of the ground roll which was determined by a surface noise test. The tube wave amplitude decreases significantly as the source is moved farther from the well head. In this case, the source array is no more important in reducing the tube wave than is the offset distance of 400 ft. A source array with more than two elements would be more effective in reducing ground roll, but VSP experiments rarely involve several source elements. A single air gun, dynamite shot, or weight drop is a common VSP energy source; rarely are there more than two sources.

This experiment was repeated at several levels in the well. One more example is shown in Figure 12: the response measured when the geophone was secured at a depth of 5000 ft. The effect of source offset on tube wave generation is more dramatic in this case, and it is obvious that increased source offset is one way to reduce tube wave amplitudes in VSP surveys. There is a modest improvement in the tube wave reduction when the source array is used, but offset is the more dominant factor in the tube wave process. The VSP data shown in Figures 2, 3, and 4 were recorded with the vibrators only 200 ft from the well which was undoubtedly too close at that well site.

A vertical seismic profile recorded in a second study well is shown in Figure 13. These data were also recorded in a borehole structured like the one in Figure 1 and have been processed to remove the effect of spherical divergence (as are the data in Figure 4). The size of the casings, the depth of the surface casing, and the cementing program in this second well are identical to those in the first well. The absence of many intervals where the recorded amplitudes of all events are abnormally high suggests that the casing string in this well may be more rigid than was the casing in well 1. The two wells are only three miles apart, and the depths of most reflectors are approximately the same in both profiles. The same Y-600 vibrators, sweeping the same frequency range of 8 to 64 Hz, were used as the energy source, and the same downhole geophone system recorded the data. The major difference in this second experiment was that the vibrators were stationed 685 ft from the well head rather than 200 ft. This increase in source offset results in a considerable reduction in the tube waves as can be seen by a visual comparison of Figures 4 and 13.

The strong primary reflection generated at 9200 ft can be seen above the tube wave zone, whereas, it could not in the first experiment. Log data from both wells indicate that the reflection coefficient for this carbonate unit is essentially the same in both wells. Since the energy input is essentially the same in both profiles, the improved reflector definition in the shallow part of the section is due primarily to reduced tube wave noise and is not the result of increased reflection energy.

**EXTRACTION OF UPGOING EVENTS BY VELOCITY FILTERING**

One of the important benefits of VSP is its ability to define the depth and surface arrival time of all upgoing seismic events in the stratigraphic section at a study well. This VSP application is an invaluable asset to seismic stratigraphy studies. The vertical seismic profile in Figure 4 represents a severe challenge to any
numerical process intended to retrieve upgoing compressional events from the data. One process that might recover these events is a properly designed velocity filter; however, the data created by velocity filtering should be used with caution in any type of waveshape analysis or attenuation measurement because of the extensive spatial compositing that occurs during the filtering process. Velocity filtered VSP data do serve, however, to mark upgoing events, to define their arrival times at the ground surface and to create reasonable estimates of the reflection waveform character that should be expected in surface measurements.

One velocity filtered version of the profile data in Figure 4 is shown in Figure 14. In order to compare these filtered data with surface reflection data, each trace is delayed by an amount equal to its first break time so that any upgoing event occurs at the same two-way time at every depth. All of the traces are then summed into a single, composited trace. This compositing tends to cancel many of the phase variations that can occur from trace to trace in velocity filtered data. The final summed trace contains all upgoing compressional events whether they are primary reflections or interbed multiples. This summed trace can then be compared with the surface seismic reflection data recorded at the well.

A comparison between the summed velocity filtered VSP data recorded in well 1 and a surface seismic line crossing the well is shown in Figure 15. The composited velocity filtered trace is labeled VSP. Also shown is the synthetic seismogram (SYN) calculated from the sonic and density log data recorded in the well. The wavelet used to construct the synthetic seismogram is an average of several of the downgoing first arrivals recorded in the VSP data, so the composited velocity filtered trace and the synthetic seismogram contain the same basic wavelet. Both the VSP trace and the synthetic seismogram are band-limited to the same frequency range, as are the surface reflection data.

In this instance, the VSP trace is a better match to the surface data than the synthetic seismogram even though the original VSP
data were heavily contaminated by tube wave noise. Some events which emphasize the match between the VSP trace and the surface data are labeled as events A through F. The VSP events down to 800 msec two-way time had to be retrieved almost entirely from the dominating tube waves in Figure 4 since they occur above 3500 ft. The ability of a well-designed velocity filter to pull signal out of this type of noise is demonstrated by the good comparison between VSP event “A” and the surface seismic response. Likewise, the VSP data contain events such as “F” that originate below the bottom of the well. Reflections occurring below the total depth of a well can never be reconstructed in a synthetic seismogram calculation.

CONCLUSIONS

The best defense against recording tube waves in a vertical seismic profile is to avoid generating them by appropriate field procedures. The field procedures should focus on reducing ground roll because there is a direct relationship between the strength of the ground roll crossing the well head and the amplitude of the downhole tube wave. The smaller the amplitude of the ground roll, the smaller the amplitude of the tube wave. Increased source offset appears to be one simple solution to reducing tube waves in the downhole recordings. Other procedures such as lowering the fluid level in the wellbore at least one seismic wavelength below the ground surface may also be effective and should be included in future experiments.

If tube waves exist in the recorded data in spite of defensive field procedures, appropriate data processing can possibly retrieve much desired information even if the tube waves tend to dominate the data. Velocity filters are probably the most powerful numerical process that can be used to extract reliable reflection information from such data. In particular, velocity filtering can emphasize
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upgoing events and serve as a valuable tool for interpreting surface reflection data.

Tube wave noise can also be reduced by synthetic vertical geophone arrays. In many VSP applications, numerically created vertical arrays should be used since they increase the S/N character of the recorded data. However, such arrays prohibit the detailed analysis of compressional and shear-wave character that can be accomplished with single geophones. If high-frequency wavelets are to be recorded, or if precise amplitude attenuation or reflection-transmission behavior are to be studied, it is not advisable to use vertical arrays. Tube wave noise must be combated in some other way.

It is important to recognize that acceptable vertical seismic profiles can be recorded in cased boreholes that are only partially cemented. This type of borehole represents the majority of the world’s existing oil and gas wells, and this knowledge opens all drilled areas to exploration via vertical seismic profiling.

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REFERENCES