ABSTRACT

Multichannel borehole hydrophone strings are a low-cost, low-risk, alternative to borehole clamping geophones. Vertical seismic profile (VSP) data collected with hydrophones, however, suffer from high-amplitude coherent tube-wave noise. This reduces the usable data to the first arrivals and traveltimes for check-shot surveys. To significantly reduce tube-wave noise from VSP data acquired with hydrophones, we have designed and tested a novel tube-wave attenuation baffle. The effectiveness of the baffle was first verified in a laboratory-scale experiment and then in a borehole drilled into a hardrock environment. The laboratory experiments tested the performance of four different baffle topologies, whereby the best performing topology was the semirigid corrugated pipe baffle. This design reduced the amplitude of the tube wave with more than 40 dB and was logistically easy to deploy. The field experiment investigated the effectiveness of three different semirigid corrugated pipe baffle topologies in a PQ (123 mm) diamond drillhole in Western Australia. Here, we found that the semirigid corrugated pipe baffle was effective in disrupting tube-wave propagation. The 100 mm diameter baffle achieved an impressive 60 dB of tube-wave attenuation, whereas the 50 mm baffle had a modest attenuation of 10–15 dB. This suggests that the performance of this new type of baffle is best when the diameter of the baffle is closely matched to the diameter of the borehole. The results of these experiments have significant implications because hydrophone arrays with a large number of receivers are comparatively inexpensive and simpler to deploy than borehole geophone counterparts. The development of hydrophone arrays that are free of interfering borehole modes could allow VSPs to be acquired in situations in which seismic-polarity information is not required and could help VSP gain traction in cases in which the cost of acquisition has precluded its use until now.

INTRODUCTION

Vertical seismic profiling (VSP) is a well-established geophysical method for evaluating seismic properties and imaging geologic structures from exploration boreholes. However, mineral exploration, engineering, and environmental boreholes are usually small in diameter (<100 mm) and are relatively shallow (100–1000 m) in comparison with petroleum wells, for which, in the most part, VSP technology has been developed. The acquisition efficiency of VSP is dependent on the number of geophone shuttles deployed, and there is a dearth of multireceiver VSP tools that are small enough to fit within boreholes drilled for mineral exploration. However, to acquire data over the entire length of a well by completely populating the borehole with receivers requires heavy surface support equipment such as a crane or a drill rig, which incur significant costs to mobilize or standby. The financial hurdles to the adoption of VSP in the mineral industry are, however, even more ingrained than this. It is important to note that mineral exploration boreholes are often drilled in difficult conditions in which the rock is strongly altered and the stability of the boreholes cannot be guaranteed. In addition, given the cost of VSP shuttles, a 24-channel string is three times greater than the cost of a 1000 m HQ (96 mm ∅) borehole, and the risk of deployment in this environment, VSP surveys in such environments are rarely acquired. This leads to a technology gap within the service sector to provide VSP at a cost that...
meets the financial means and risk profile of the mineral exploration geophysicist.

An alternative seismic receiver to the borehole clamping geophone is the borehole hydrophone. These are small, lightweight, highly sensitive broadband pressure sensors that do not require clamping to the borehole wall. This makes hydrophones a logis-

tically quicker less complex solution and the idea to use hydrophones for acquisition of VSPs has been around for several years (e.g., Huang and Hunter, 1984; Marzetta et al., 1988; Milligan et al., 1997). However, hydrophones do not provide the same richness of information that a 3C clamped geophone can provide, such as, for example, the separation of horizontal and vertical S-wave motion, and the determination of anisotropic properties in the borehole annulus. In addition, the hydrophone VSP experiment is very suscep-
tible to borehole guided waves known as tube waves that are one to two orders of magnitude larger in amplitude than seismic body waves (Cheng and Toksöz, 1982). These tube waves overlap the desired reflected and late-arriving wavefields in the VSP profile, and, as a consequence, the use of borehole hydrophone arrays has mostly been limited to velocity checkshot and tomography sur-

veys (e.g., Greenhalgh et al., 2000; Gulati et al., 2001). This is not to say that tube waves do not carry useful information. They are often generated at large impedance contrasts in the borehole annulus (White, 1983) such as open fractures. Because of this causal link to open fractures, tube waves have been used in the detection and characterization of fractures by several authors (e.g., Toksöz et al., 1992; Li et al., 1994; Ionov and Maximov, 1996; Greenwood et al., 2017). Moreover, the determination of hydraulic properties through numerical modeling of tube waves is an active field of research for several authors (e.g., Bakku et al., 2013; Minato et al., 2017).

In the case of VSP imaging, tube waves and other parasitic modes are seen as noise. The quality and quantity of information obtained from the VSP therefore depend on our ability to separate the useful seismic modes from the parasitic modes. As we will see later, it is possible to mitigate some of the impact of tube waves at the acquis-
tion stage through survey design (e.g., Hardage, 2000), with the use of downhole baffling solutions (e.g., Pottier, 1992; Pham et al., 1993; Milligan et al., 1997; Minto, 2001; Daley et al., 2003) or with judicious postprocessing efforts (e.g., Marzetta et al., 1988; Greenwood et al., 2012). However, current baffling solutions are either depth limited due to increasing hydrostatic pressure or they require the addition of complicated pneumatic gas lines downhole. Postpro-

cessing methods for the attenuation of tube waves require the wavefield to be densely sampled spatially (<3 m); otherwise, they can introduce undesired artifacts into the VSP records. As such, the large disparity between tube wave and seismic reflection amplitudes remains a concern for hydrophone VSP imaging.

The aim of the current work is to propose a tube-wave mitigation strategy that can be deployed during the acquisition of the data and thus reduce the demands on the postprocessing efforts and improve the overall signal-to-noise ratio (S/N) of VSP records acquired with hydrophones. To attenuate the transmission of the tube-wave energy, the particle motion along the borehole axis must be disturbed. For this, we propose a semirigid corrugated pipe baffle that fills a portion of the fluid annulus. The concept behind the use of semi-
rigid corrugated pipe baffle is to progressively interfere with particle displacement in the fluid as the tube wave propagates through the baffle. This approach is not depth limited because the borehole fluid is free to flow in and out of the baffle; thus, there is no differential

pressure inside and outside of the baffle. Therefore, unlike previous foam baffles that collapse at depth, the attenuative characteristics of the baffle system remain unaffected by the increased hydrostatic pressure.

This work is composed of three parts. First, we present a short review of the origin of tube waves and the mechanisms that generate them to motivate the development of an attenuative baffling system. Then, we briefly report on the current state of the art in tube-wave suppression and removal by numerical methods. Third, the effec-
tiveness of the semirigid corrugated pipe baffle design is evaluated in a laboratory setting alongside other potential baffling solutions. The success of the laboratory experiments motivated a field test of the semirigid corrugated pipe baffle in a hardrock borehole located near Kambalda, Western Australia. The outcomes of the test are documented in the final part of this work and discussed in relation to the potential advantages, disadvantages, and logistical implemen-
tation of corrugated pipe baffles in small-diameter boreholes.

**TUBE-WAVE PROPERTIES**

Tube waves are low-frequency Stonely waves that propagate along the borehole as guided waves (Cheng and Toksöz, 1981, 1982). They appear in the VSP record as coherent linear events (Figure 1a) as the borehole receivers are populated along the axis of the tube-wave propagation. Tube waves originate from the inter-

action of seismic body waves with large changes in the borehole setting (Hardage, 1981). The common generation mechanisms are the Rayleigh wave and other body waves, passing the top of the borehole fluid (Gal'perin, 1974), as well as at marked variations in the diameter of the borehole, and at large acoustic impedance changes within the borehole annulus, such as the bottom of the borehole and the termination of any casing material. In addition, an incident P-wave (or SV-wave) compressing a compliant open fracture that is intersecting the borehole (Huang and Hunter, 1984), induces a pres-

sure pulse into the fluid column. That in turn, generates a down- and an upgoing tube wave. These mechanisms are also the catalysts for the reflection, and subsequent weakened transmission, of tube-wave energy. These mechanisms are illustrated in Figure 1b–1d.

From the work of Biot (1952) and White (1965), we know that tube waves can exist at all seismic frequencies and that they are only slightly dispersive. As shown by Beydoun et al. (1985), tube waves have a velocity of approximately 0.9 times the fluid velocity at low frequencies and increasing toward the fluid velocity with higher frequencies and higher shear moduli. A tube wave has a phase velocity that is lower than the formation S-wave and fluid velocity (Beydoun et al., 1985). They do not undergo geometric spreading, and their amplitude decays away from the borehole wall in the fluid and formation (Cheng and Toksöz, 1982). Thus, disturbing propa-

gation along the borehole wall is an important element for any mitiga-

tion strategy.

The particle motion associated with tube waves in the borehole fluid is elliptical away from the borehole wall, and it is pure recti-

linear in the center of the borehole as demonstrated in Figure 2a. The radial axis of displacement is continuous at the borehole bound-

ary, whereas the axial component is discontinuous at the interface (White, 1983). The axial component of motion is much larger than the radial component, and in hard formations, it is larger within the fluid column by a factor of 20 at 400 Hz and a factor of 100 at 75 Hz as demonstrated by Cheng and Toksöz (1982) in Figure 2b and 2c. Consequently, clamping geophone data are comparatively tube-wave
free because it measures the particle motion at the borehole wall, whereas a hydrophone measures the pressure differences caused by particle motion in the fluid column. Thus, any means to suppress particle motion within the fluid column is highly desirable to enable VSP imaging using a hydrophone array.

**TUBE-WAVE MITIGATION: STATE OF THE ART**

Tube-wave mitigation strategies can be implemented actively or passively during acquisition or postacquisition with processing methods. Active strategies have been conceived to combat the Rayleigh-wave generated tube wave through survey design, including (1) distancing the shot from the borehole, (2) lowering the fluid level in the borehole below the zone of influence of the source-generated Rayleigh waves, or (3) digging trenches between the shotpoint and the top of the borehole collar (Hardage, 2000). Although these strategies can lead to a reduction in tube-wave contamination of the VSP record, in some circumstances, they impose difficult constraints on the acquisition geometry and complicate land access requirements. They are also less desirable in near-surface investigations when the intent of the VSP survey is to determine the true interval velocity because the seismic source must be placed in close proximity to the borehole collar. Furthermore, these strategies do not combat tube waves generated by other body waves passing the top of the fluid column. In addition, when multiple positions of the hydrophone array are required to survey the entire borehole length, a significant difference in the arrival time of the fluid-top tube wave can be observed due to the displacement of water caused by changing the volume of the survey cable in the borehole. This has been noted by Greenwood et al. (2011) when surveying a 1000 m borehole with a 24-channel 10 m spaced hydrophone array, whereby a full array move constituted an effective volumetric change of cable in the borehole of 96e-3 m³ or approximately 8 m for a hole with a diameter of 123 mm. In these situations, we would advise to flood the borehole, if it is not losing water, to maintain the water level at a constant position. Obviously, there should be no pumping during the recording periods.

The second active mitigation strategy is to isolate the hydrophone array from down- or upgoing tube waves within the borehole. This can be achieved by inserting high-acoustic-impedance items strategically in the borehole that reflect the tube-wave energy away from the array. In general, this high acoustic impedance takes the shape of some form of bladder made of rubber or a polymeric expandable material filled with compressed gas such as air or nitrogen. The Bolt Technology Corporation implemented such a method described by Chelminski (1989) to isolate tube waves generated from a downhole source. This was then adapted by Minto (2001), whereby a partially filled gas cylinder was placed above and below the borehole receiver array, to isolate the array from the fluid-top and borehole-bottom generated tube waves. This idea was revisited by Daley et al. (2003), who achieved a 23 dB improvement in S/N with an inflatable bladder placed above their hydrophone receiver array. Several other bladder shapes and diaphragms to accomplish isolation of the receiver array have also been proposed by West and Haefner (2004).

These active isolation methods can conceivably be deployed at any depth, however, they incur significant logistical difficulties requiring gas lines and sufficiently large boreholes for deployment. In

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**Figure 1.** (a) Identification of different tube wave origins in the VSP profile and the mechanisms that generate them. (b) Fluid-top tube wave generated by a Rayleigh wave, (c) tube wave generated at an open fracture intersecting the borehole, (d) reflection and transmission of a downward propagating tube wave at a change in borehole radius, and (e) the reflection and transmission of a downward propagating tube wave at a change in acoustic impedance within the borehole annulus.

**Figure 2.** Tube-wave propagation in a borehole. (a) Prograde elliptical particle motion in the fluid column and the formation associated with tube-wave propagation along the borehole wall (modified from Hardage, 2000). (b and c) Axial and radial displacement amplitudes in the fluid and a hard formation calculated at 409 and 82 Hz (after Cheng and Toksöz, 1982).
addition, they suffer from a fundamental weakness in hardrock environments in that, although resilient to the passage of energy that originate from above and below the array, it cannot attenuate tube waves that are generated at fractures within the measurement interval.

The passive strategies proposed can be classified as attenuative solutions, in which an acoustically absorptive material is placed within the borehole to diminish tube-wave noise. Among the materials tested we find the following: the use of cork, in the form of disks and balls as an attenuator housed within a cylindrical container (Potier, 1992); the use of syntactic foam within a cylindrical housing to form a porous but impermeable body placed between the source and receivers (Pham et al., 1993); closed-cell-foam baffles (Milligan et al., 1997) placed above, below, and in-between hydrophone elements on an array, as well as; rigid porous conical baffles with interconnected pores developed by Hsu et al. (1997).

All of these solutions share a common idea and also common flaws that make their performance either depth dependent and or potentially difficult to deploy. First, as the hydrostatic pressure increases in the borehole, the baffling material tends to collapse onto itself and thus its ability to absorb the energy is reduced. A good example of this phenomenon is illustrated in the work of Milligan et al. (1997) who successfully attenuate tube waves with interhydrophone baffles until a depth of 50 m was reached and the foam collapsed. Perhaps an alternative is to use open-cell baffles. Second, the baffle must occupy a significant cross section of the borehole to be effective, and although the baffles are porous, water flow in, out, and around the baffles is restricted, thus requiring long deployment and extraction times.

Postacquisition numerous wavefield separation methods have been developed for VSP and seismic imaging, which can be applied for the separation of tube waves. Among the most successful and commonly used methods are 2D spatial filtering, $f-k$ velocity filtering, slant stack or $\tau-p$ filtering (Hinds et al., 1996), wavelet modeling (e.g., Blias, 2007), and singular-value decomposition (e.g., Teakle et al., 1995). Of these methods, the most common is that of 2D spatial filtering, which requires very accurate time picking and alignment of the target wavefield to sum over before removal. In addition, 2D spatial filters suffer from edge effects as traces drop out of the filter window. These effects can be minimized by changing the Hilbert window size at the edges (Marzetta et al., 1988), but more importantly by increasing the number of traces, which requires either larger channel counts or high source repeatability. With respect to the velocity and $\tau-p$ filtering methods, spatially well-sampled data are required to avoid aliasing. Marzetta et al. (1988) successfully demonstrate the use of velocity filters to remove tube waves from a 96-trace hydrophone VSP profile. To achieve this, a hydrophone spacing of 1.5 m was used to sample the tube-wave noise adequately. Greenwood et al. (2012) successfully use a modified wave-by-wave wavelet subtraction (Blias, 2007) on spatially aliased tube-wave data, collected with a 10 m spaced hydrophone array. Despite this significant achievement, the wavefield

Figure 3. Laboratory experimental procedure and baseline results. (a) Schematic of the PVC test rig, hydrophone suspension, the different acoustic and corrugated pipe baffle topologies tested (insert), and the source exciting surface waves. (b) Baseline data collected with a single hydrophone at 0.05 m depth intervals. Note: Depth is plotted in reverse as the primary waves travel from the bottom to the top of the tube.

Figure 4. Laboratory results for the tube wave baffling configurations described in Figure 3. All baffle topologies have successfully attenuated the borehole-bottom tube wave as indicated by the red ellipsoid. In addition, the top and bottom corrugated pipe baffle configuration has removed the fluid-top tube wave indicated by the dashed ellipse in (e).
separated hydrophone data are of less fidelity than a comparative 3C-geophone data set collected in the same borehole. Furthermore, the data set contains artifacts caused by strong overlapping (opposing direction) tube waves. In brief, no single method is completely successful in removing strong coherent tube-wave data from VSP profiles without leaving some artifacts, and the success of any processing method is dependent on the quality and repeatability of the field data. In addition, it is necessary to trial different filters and filter lengths to enhance exactly the features that are needed for the interpretation (Kommedal and Tjøstheim, 1989).

All of the above mitigation strategies have had a measure of success but did not completely eliminate tube waves. The solution we have developed in this work registers in the camp of passive attenuative solutions, and it works via the introduction of rugose corrugations in the vicinity of the borehole wall where fluid particle motion is strongest. In addition, the semirigid corrugated pipe baffle is hollow, which allows water to freely flow inside of the baffle, not limiting the baffles effectiveness at increasing depth, aiding movement in the borehole. The experimental data presented below assess the merit of this approach for sparsely sampled hydrophone data.

**LABORATORY EXPERIMENT**

To determine the effectiveness of baffles constructed from acoustic absorptive mediums and semirigid corrugated pipe, we devised a simple laboratory experiment. A 3 m PVC pipe with a 44.1 mm internal diameter was capped with a standard plumbing cap and filled with fresh water. This test apparatus was housed in a shed at the Australian Resources Research Centre. A Schmidt hammer was used as a seismic source, and an in-house hydrophone (bandwidth of 1–2500 Hz) was used as the receiver. The source was placed 1.1 m from the test apparatus, and both rested upon the concrete slab of the shed. Figure 3a illustrates the experimental setup. An Omega acquisition unit (OMB DAQ 3001) was used to digitize the signals at a rate of one sample per 5 μs. Triggering of the acquisition system was assured via an in-house piezoelectric transducer.

To validate that our test apparatus was able to generate and record tube waves, we lowered the hydrophone into the fluid filled column in increments of 5 cm to a total depth of 1.55 m. At each depth, two shots were recorded and later stacked to improve the S/N of the measurement. The data that resulted from this test are seen in Figure 3b. In these data, we can clearly identify the first-arrival PVC P-wave (1760 m/s), the reflected P-wave (1760 m/s), as well as two tube waves, namely, the borehole-bottom tube wave generated by ground roll passing the water column and a tube wave generated at the fluid top. The observed tube-wave velocity of 377 m/s is consistent with the predicted tube-wave velocity in a cased borehole with velocity $V_{te} = 375$ m/s obtained from equation White (1953):

$$V_{te} = V_f \left[ \frac{1}{\sqrt{1 + \frac{K_f D}{4 \pi f^2} \frac{d^2}{D^2}}} \right],$$

where $V_f$ is the fluid velocity (1480 m/s), $K_f$ is the bulk modulus of the fluid (2.2 × 10^9 Pa), $D$ is the diameter of the borehole (48.25 × 10^{-3} m)

![Figure 5. Amplitude and attenuation results for the baffle topologies tested. (a) Raw tube wave signal strength picked along a common time horizon. (b) Absolute and (c) average attenuation calculated from the signal strength regression lines.](image)

<table>
<thead>
<tr>
<th>Borehole</th>
<th>O.D. (mm)</th>
<th>I.D. (mm)</th>
<th>Relative surface ratio</th>
<th>Slot size (mm)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BQ</td>
<td>60</td>
<td>44</td>
<td>0.16</td>
<td>1.25 × 4</td>
<td>0.175</td>
</tr>
<tr>
<td>NQ</td>
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<td>55</td>
<td>0.21</td>
<td>1.25 × 5</td>
<td>0.23</td>
</tr>
<tr>
<td>HQ</td>
<td>96</td>
<td>68</td>
<td>0.19</td>
<td>1.25 × 5</td>
<td>0.35</td>
</tr>
<tr>
<td>PQ</td>
<td>123</td>
<td>86</td>
<td>0.17</td>
<td>1.25 × 7.4</td>
<td>0.475</td>
</tr>
</tbody>
</table>

Note: The drill rod dimensions are extracted from Boart-Longyear (2011).
Our baffling experiment considered four different baffle configurations to test their effectiveness. The length of the baffles was chosen to be on the order of one wavelength of the tube wave $\lambda$. This length was easily computed given the relationship among velocity, wavelength, and frequency. In our case, the observed dominant frequency of the tube wave and its velocity were 2100 Hz and 377 m/s, respectively, and thus the baffles were made 18 cm in length. Interestingly, this length also corresponds approximately to $\lambda/4$ of a P-wave in water at the same frequency.

The first two baffles to be evaluated were constructed of dental putty ($1.44 \text{g/cm}^3$) cylinders ($30 \times 20 \text{mm} \bigcirc$) linked together with a string and suspended at the bottom of the hydrophone. These two baffles differed only in that the second baffle had additional 22 mm diameter metallic washers inserted between the dental putty cylinders. The third and fourth baffles to be tested were constructed out of semirigid polyethylene corrugated pipe ($180 \times 28 \text{mm} \bigcirc$ with 210 corrugations/m). The difference between the third and fourth baffle experiment was in the baffle topology. In one case, the semirigid corrugated pipe baffle was placed only below the hydrophone, whereas in the other, it was placed above and below. The baffle arrangements are summarized in the inset of Figure 3a.

The procedure described in the verification of the test apparatus was repeated for every baffle configuration. The data measured during these four experiments can be found in Figures 4 and 5. From these results, it is possible to appreciate that all of the different baffles provide some level of attenuation of tube waves but some perform better. It is also important to note that the baffles do not interfere with the arrivals of the P-wave reflection, and this truly improves the S/N of the records. The maximum amplitudes of the downgoing tube-wave arrivals are sampled from the data in Figure 4 and compared in Figure 5a to quantify the performance of the baffles. Two attenuation results for each baffle are calculated; the attenuation using the absolute signal strengths before and after baffling (Figure 5b), and second, the attenuation between the signal strength trends (Figure 5c) to partially account for erroneous signals from overlapping wavefields. The dental putty on its own succeeded in attenuating the downgoing tube wave by a very respectable 40.6–36.2 dB (raw ~ trend line), and the addition of steel washers improved the attenuation to 46.5–42.2 dB. Coincidentally, the ratio of improvement between these two baffle configurations is approximately equal to the increased relative surface area of the baffle with and without the steel washers. In this context, we believe that the solid-type baffle acted more as an isolation-style baffle, not an attenuative baffle as intended. The corrugated pipe baffle for its part attained an attenuation of 46.3–42.7 dB and when placed above the hydrophone removed the best part of the upgoing tube wave as shown in Figure 4e.
These results illustrate the merit of semirigid corrugated pipe baffles. In addition to achieving the highest mean attenuation of the tube waves, they are also the easiest to retrofit to hydrophone arrays and to deploy. Because they are hollow, they can easily slide in place. They also have the advantage of taking up less volume in the borehole and therefore minimize the chances for pressure differentials to form above and below the baffles. Thus, there is less risk to jeopardize the retrieval of the hydrophone string. For all of these reasons, only the semirigid corrugated pipe baffles were retained for testing under field conditions.

FIELD VALIDATION

A suitable borehole for our trials was identified at BHP Billiton Martha’s Vineyard Nickel prospect, 7 km north of Kambalda, Western Australia. The uppermost portion of the borehole was drilled in competent mafic and granite units that ensured a safe testbed for the baffle experiments. It had a PW steel casing with a diameter of 149 mm to a depth of 33 m and was then drilled to a depth of 1064 m with PQ drill rods (123 mm diameter). Further geology and background of the VSP test site can be found in Greenwood et al. (2012).

The most suitable material for the construction of our semirigid corrugated baffles that were readily available at the time of the experiment was agricultural irrigation piping. Molded from polyethylene, it was available in several sizes and standard lengths of 100 m rolls. We chose to trial two different diameter baffles to determine their effectiveness. The first with an internal and external diameter of 55 and 65 mm, respectively, and the second with an internal and external diameter of 86 and 100 mm, respectively. The common sizes of agricultural piping available at the time of the experiment are juxtaposed with common diamond drilling pipes available at the time of the experiment and are listed in Table 1. In Table 1, we also find the linear weight of the baffling material and the relative surface area.

The choice of the two different sizes of baffles was imposed by logistic considerations. The more volume that a tool occupies in the borehole, the more chance it has to becoming stuck (i.e., debris dislodged during positioning of the tool may interfere with the progression of the tool). Given the considerable investment represented by the borehole and our experience in deploying this type of hydrophone array, we erred on the side of caution for these initial trials in the uncased portion of the borehole. The larger size baffle mentioned previously was never deployed fully outside of the casing in which there was increased risk of dislodging debris and or not re-entering the casing. The smaller-size baffle was chosen such that it would easily pass through the larger 100 mm baffle. Photographs of the installation and deployment are shown in Figure 6.

Our receiver array for this field trial was made of 24 hydrophones molded at 10 m intervals onto a 1000 m purpose-built multipair cable that brought the analog signals back to the surface, where they were digitized using a 24-channel seismograph (DAQ-Link). In addition to this equipment, we placed a foam damper arrangement at the top of the borehole collar. This foam damper is constructed of a custom clamping system that mounts onto the cable once the hydrophone array is positioned at the appropriate depth. Once the clamp is installed, it is made to rest on an arrangement of wood and foam, which suspends the cable and isolates it from surface vibrations. The hydrophone cable is also slacked considerably to ensure good acoustic isolation among the hydrophone array, the tripod, and the recording truck.

The 9.5 m long baffles were installed onto the hydrophone array with the help of the slotted cone and disc assembly illustrated in Figure 7. The installation of the baffling involved sliding the hydrophone array inside the semirigid baffle using a 10 m piece of poly-pipe. The top and bottom of each baffle were secured with a slotted cone and disc assembly as shown in the photo in Figure 7. This was efficiently achieved using self-tapping screws and a battery-powered drill in approximately 1.5 h. The 50 mm baffles were kept on the hydrophone string after the experiments and stored in a crate alongside the winch housing. This required some manual handling but was easily accomplished by one person.

Four baffling permutations were tested during these trials as illustrated in Figure 8. The first no-baffle baseline set of measurements was recorded over an interval that spanned 25–255 m. To better spatially sample the seismic signals, the array was raised by 5 m to span the interval between 20 and 250 m. These two shot records were then merged together to obtain one shot record that spans from

![Figure 8](https://example.com/figure8.png)

Figure 8. Field setup and baffle topologies tested. A schematic of the foam and plywood damping system (brown) used to suspend the hydrophone string on top of the steel casing (blue) is shown upon the casing. The hydrophone string is the thick dashed-dotted line, whereas the 50 and 100 mm baffles are shown as the thick checker board and horizontal stripes, respectively. The depth is shown on the left, and a general lithology column and natural gamma log of the borehole are provided to the right. The dashed shaded boxes indicate the depth windows used for the respective amplitude and attenuation analysis.
20 to 255 m sampled at an 5 m increment. The resulting baseline shot record is found in Figure 8. This 5 m acquisition procedure remained constant during all of the experiments. A 45 kg accelerated weight drop was used as the seismic source, and multiple repeat shots were taken and stacked postsurvey after bad trace/record editing. In the second experiment, a 100 mm × 50 m long baffle was deployed to span the interval between 0 and 50 m as illustrated in Figure 6c, exposing 17 m of the 100 mm baffle to the uncased borehole. In the third experiment, the 100 mm baffle was removed from the borehole and the 50 mm baffle was installed between the 12 bottom hydrophones of the array (140–255 m), whereas the top 12 (20–135 m) remained unbaffled as illustrated in Figure 8b. For the final experiment, the 100 and the 50 mm baffles were combined in the arrangement described previously for the second and third experiment, and the results are illustrated in Figure 8d. The data were grouped into two subsets for analysis. Experiments 1 and 3 are grouped as the 50 mm baffle analysis (Figure 8a and 8b), and experiments 1, 2, and 4 are grouped as the evaluation of the 100 mm baffle (Figure 8c and 8d). These two analysis groups used independent trace windows from 180 to 255 and 80 to 135 m, respectively, as indicated in Figures 8 and 9.

Installation of the 50 mm baffle for experiments b, c, and d increased the effective weight of the hydrophone array and unexpectedly enhanced cable waves. To reduce these waves, additional foam damping was appended to the...
collar mount (Figure 8) and has been labeled as double mount (DM), as opposed to single mount (SM), throughout the manuscript. The enhanced cable waves and effects of additional dampening can be seen in Figures 10 and 11. The 50 and 100 mm baffle experimental results (Figures 10 and 11) were carefully trace edited and amplitude balanced before any quantitative analysis. The amplitude balancing procedure and results are presented in Appendix A for reference.

**ANALYSIS OF FIELD DATA**

Qualitative visual inspection of the 50 mm baffle experiment results in Figure 10 does not indicate any obvious perceivable reduction in tube-wave amplitudes, with only a slight diminishing of the background amplitudes as shown by the dimmer grayscale. However, the addition of the baffles does appear to give a slight improvement in the S/N as seen by the cleaner more coherent tube-wave arrivals in the baffle sections. On the other hand, there are outwardly obvious differences in the 100 mm baffle data presented in Figure 11. In addition to the previously discussed cable-wave noise, there is a distinct removal of the casing and fluid-top tube wave that manifests between 300 and 360 ms across all the 100 mm baffle

<table>
<thead>
<tr>
<th>Baseline</th>
<th>100 SM</th>
<th>100 DM</th>
<th>100 + 50</th>
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</table>

Figure 11. The 100 mm baffle experiments normalized using first-break amplitudes from the channels 8–12 prestacked field records. The additional weight of the 50 mm baffles (suspended below the analysis window) induced cable waves in the SM and DM data. Additional mounting (DM) has only partially suppressed the induced cable waves.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>50 SM</th>
<th>50 DM</th>
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Figure 12. (a) Trace-balanced 50 mm baffle experiment data and (b) after filtering with a Butterworth 12 dB/octave filter. The P-wave first arrival (magenta), a fracture-induced tube-wave event (red), the fluid-top tube wave (blue), and the casing tube wave (green) horizons have been picked with their respective amplitudes graphed below.
experiment results. Furthermore, there is a removal of the cable waves in the 100 + 50 mm baffle topology data. The cable waves are assumed to have been reflected and scattered via the creation of multiple nodes along the hydrophone string, generated by the 50 mm baffle being in contact with the 100 mm baffle. The remaining tube waves in the 100 + 50 mm data, originate from below the hydrophone string; thus, they have not interacted with the 100 mm baffle. These upgoing tube waves are then seen to be reflected down from the bottom of the 100 mm baffle as indicated in Figure 11 by the dashed black lines.

Quantitative amplitude analysis of the different baffle topologies is conducted over three individually defined tube-wave events in the 50 and 100 mm data sets. In general, the most coherent first three events were chosen for the analysis, whereby arrival times are picked along peak events in the baseline data and are then used to attain amplitude differences within the baffled data sets using a time window between 0.2 and 1.0 ms. Signal strength variations have been plotted for the chosen tube-wave events, and the attenuation with respect to the baseline data is calculated. Linear regression lines have been fitted to the signal strength and attenuation data with the respective $R^2$ values computed. In addition, a proxy for average attenuation has been determined via the differences in the linear regression data. The picked horizons and signal strengths are shown in Figures 12 and 13 for the 100 and 50 mm trials, respectively. Due to the weak response of the 50 mm baffle and the strong overlapping cable waves in the 100 mm baffle experiments, attenuation results for the 50 and the 100 mm uppermost (red) tube-wave event are not presented here. These omitted results, however, are available in Appendix B.

The attenuation results of the 100 mm baffle experiments for the green and blue events are shown in Figure 14. We see in this figure that multiple overlapping wave modes exist in the field data, which complicate the determination of the true tube-wave event and subsequently measure the suppressed amplitudes. As such, many of the amplitude picks are erratic, as shown in Figures 12–14, and lead to very low $R^2$ values (Appendix B). However, very respectable attenuations ranging between 20 and 60 dB have been achieved for all the 100 mm baffle and collar mounting configurations (Figure 14). The 100 mm baffle on its own achieved an average attenuation of 33 dB and with the inclusion of the 50 mm baffle increased the suppression to approximately 49 dB for the chosen tube-wave events.

Power frequency relationships have been calculated for the 100 mm baffle experiments and are displayed in Figure 15. Similar plots for the 50 mm baffle experiments can be found in Appendix B. The power spectrum per trace and the power spectral density plots show clear differences in power per frequency. The baffled data are arguably less noisy, there is coherent high-frequency content in the 100 SM and 100 DM data that can be attributed to cable waves, and the 100 + 50 mm power spectral density data show a clear reduction in frequency at later times. The reduction in power at later times is attributed to the removal of high-amplitude tube waves. This reduction of power at late times and the preservation of power at early times (P-wave signal) is also seen in the spectrograms of the traces at 120 m depth. These results clearly demonstrate the effectiveness of a

![Figure 13](https://pubs.geoscienceworld.org/geophysics/article-pdf/84/3/D131/4707254/geo-2017-0636.1.pdf)
**DISCUSSION**

Fluid particle displacement associated with tube waves is highest at the borehole wall (Figure 2); thus, it is reasonable to expect that corrugations would be their most effective at disrupting particle displacement when they are placed in close proximity to this interface. As such, the attenuative effect of the corrugated pipe baffle is likely proportional to the ratio between the diameter of the baffle and the borehole. The relative corrugation depth (the difference between the baffle inside and outside diameters) and the number of corrugations per meter must also play a role, but these factors could not be permuted in our experiment. The effect of the ratio of diameter of the baffle to that of the borehole is well-supported by the experimental data and as anticipated, the 50 mm on its own has less impact (7 dB) than when it is used in conjunction with the 100 mm baffle (50 dB), or in comparison to the 100 mm baffle on its own (33 dB). To further illustrate this point, we can compute the relative cross-sectional area of the semirigid corrugated baffle by considering its inside and outside diameters and compare this with the cross sectional area of the PQ borehole. Doing this, we find that, the 100 mm baffle disturbs 16% of the water column at a periodicity of 80 corrugations/m. This is significant compared with the 50 mm baffle that has a surface area relative to the PQ borehole of only 3.2% and a periodicity of 170 corrugations/m.

We initially anticipated that the 50 mm continuous baffle would lead to greater attenuation because it had the greatest length of all the baffles at 120 m and therefore would interact for the greatest amount of time with the tube waves. The 50 mm attenuation and power spectrum plots (Appendix B), however, do not show any steadfast trend to support the hypothesis that the overall length of the baffle plays an important role in the amount of attenuation achieved for the downgoing tube waves with depth. It is expected that a larger analysis window without any overlapping wavefields may reveal a more reliable trend, but the qualitative evaluation of the results show mitigated success. Interestingly, however, we can see that higher frequency noise events are suppressed by the 50 mm baffle. We believe that this reduction can be attributed to a quieter fluid column, likely due to the presence of the baffles.

It is important to note that it was impossible in this experiment to completely reproduce the circumstances of the laboratory experiment and thus that the length of our baffles was possibly suboptimal. In the laboratory experiment, the frequency of the signal and the velocity of the tube wave made it possible to construct baffles that were a full $\lambda$ in length. In the field experiments, the lower seismic frequencies $f_0 = 80$ Hz and the higher tube-wave velocities $V_{tw} = 1480$ m/s (for the hard formation) result in longer wavelengths $\lambda \approx 40$ m that are four times greater than the individual 50 mm baffles and twice as long as the 100 mm baffle. Thus, we have maintained at least a 0.25 $\lambda$ at all times, and the combined 50 mm baffle is approximately 3 $\lambda$ (120 m) in length.

It is noted that the corrugations generate turbulent drag during deployment and removal. This slows down acquisition and increases the stress on the hydrophone cable. The drag is directly related to the corrugation depth, their periodicity, and the length of the baffles. Although we did not experience any great increase in array move times when deploying/retrieving the 50 mm baffles, we expect that this would be significantly different in either a smaller NQ or BQ borehole, or conversely with a much longer 100 mm baffle in the PQ borehole. Our general experience with hydrophone arrays and tube-wave mitigation, however, would tend to the construction of an array with 2.5 m spaced hydrophone elements for hard rock environments (Greenwood et al., 2011), which would result in a total baffle length of 60 m for a 24-channel system, thus reducing the total drag and array repositioning times.

![Figure 14. Attenuation analysis of the 100 mm baffle field experiments. 100SM: single collar mount data, 100DM: double collar mount data, and 150: the 100 mm with the 50 mm baffle included. Attenuation has been determined from (b) the signal strength peak values as well as between (c) the average amplitude trend lines.](https://pubs.geoscienceworld.org/geophysics/article-pdf/84/3/D131/4707254/geophysics-2017-0636.1.pdf)
Figure 15. Power frequency spectrums for the 100 mm baffle field experiments displayed from top to bottom as unfiltered experimental data, power spectrum per trace overlapped with each other, individual power spectrum per depth/trace, and the spectrograph of the trace at 120 m depth for each baffle experiment.
There are downsides to semirigid corrugated baffles. The first is the requirement to maximize the baffle diameter to increase the suppression effectiveness of the baffle. Matching the outside diameter of the baffle to the inner diameter of the borehole raises concerns about potential obstruction and the dislodgement of debris, which could render the array stuck in the borehole. As with all borehole geophysical surveys, the structural integrity of the borehole should be ascertained prior to any tool deployment. Our results suggest that a baffle to borehole diameter ratio of 0.8 is sufficient to achieve good attenuation and leave sufficient operational space in the borehole. In addition, the baffle material is semirigid and thus somewhat deformable should debris be dislodged into the fluid column. The semirigid structure could be weakened by creating multiple vertical cuts in the baffle, thus allowing debris to fall into the baffle and allowing free movement of water, while maintaining its attenuative properties. Alternative mitigation strategies could also be engineered into the baffle clamps, such as rock catchers and shear pins.

An alternative corrugated pipe baffle solution could be to baffle the borehole (partially or fully) postdrilling, as demonstrated with our 100 mm baffle experiment, and survey through the baffles. This would serve to protect the borehole from collapse, eliminate potential tool loss, and remove any drag concerns. However, the baffle would need to be installed after any geophysical surveys that require direct contact with the formation such as full waveform sonic, caliper, optical and acoustic televiewer logs. This strategy also assumes that the seismic body wave pressure signals are efficiently transmitted and unaltered by the presence of the baffle between the borehole wall and the hydrophone element. Greenwood et al. (2018) show this to be feasible when conducting a walk-away hydrophone VSP through slotted PVC casing; however, additional laboratory and field experiments should be conducted to ascertain, if or what, changes in signal phase and amplitude arise.

CONCLUSION

To date there is no one complete solution to tube-wave mitigation and hydrophone VSP surveys require careful acquisition design and execution to minimize tube-wave contamination. Here, we have shown that semirigid corrugated pipe baffles effectively disturb fluid motion at the borehole wall and diminish the tube-wave energy. The attenuative effect of the semirigid corrugated pipe baffle is directly related to its size relative to the borehole and its proximity to the borehole wall. We observed the most effective tube-wave suppression of approximately 50 dB within a 123 mm diameter borehole, using a cocentric baffle arrangement in which a 50 mm baffled was placed inside a 100 mm baffle. The larger diameter baffle on its own led to an average 33 dB reduction in tube waves, whereas the smaller diameter baffle (50 mm) by itself did not significantly affect the propagation of the tube wave (7 dB reduction).

These baffles are easily retrofitted to existing hydrophone arrays and can be deployed to any depth because there is no hydrostatic pressure differential between the inside and outside of the baffle system because water is allowed to freely flow from each domain. However, an appreciable increase in drag is experienced during the deployment and retrieval of the array.

It is possible to deploy a hydrophone array through a sufficiently large corrugated pipe baffle that is predeployed into the borehole. Such a strategy can be used to mitigate the casing and fluid-top tube waves. In addition, a semirigid corrugated pipe baffle could be sunk to the bottom of the borehole to combat the borehole-bottom tube wave.

The added weight of the baffle system enhanced the effects of cable waves, an important result to note when planning field experiments and mitigation strategies. In addition, further studies are required to optimize baffle geometry and quantify the relationships among attenuation, corrugation periodicity, and depth of corrugation.

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DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.

APPENDIX A

ENSEMBLE BALANCING

Individual field records were ensemble balanced after bad trace editing and before stacking. In the absence of a reference geophone, the data sets were normalized using a selection of un baffled channels. The 50 mm data were ensemble balanced using the average amplitude of the tube wave at 150 ms between depths 90 and 150 m (channels 7–12) as shown in Figure 8, and the results are shown in Figure A-1. A similar approach was used to ensemble balance the 100 mm baffle experiment data; however, it was not possible to use amplitudes from the strong coherent fluid-top tube wave as experiment d has 50 mm baffles within the amplitude analysis window (Figure 6). As such, ensemble balancing was performed using a selection of coherent first arrivals between 100 and 150 m depth. The 100 mm ensemble balanced data are shown in Figure A-2.

APPENDIX B

50 MM ATTENUATION DATA

Signal strength variations and attenuation estimates for the 50 mm baffle experiments are ascertained using the same procedure as described for the 100 mm baffle experiments (the “Analysis of field data” section) and are presented in Figures B-1 and B-2. Similarly, the power frequency relationships are presented in Figures B-3 and B-4. The attenuation observed in Figures B-2 and B-3 is appreciably low; however, across all tube-wave events, some attenuation has occurred with attenuation mostly between 5 and 15 dB. There is no clear separation in the results with respect to the baffles having performed better on any particular tube-wave event; however, one could argue that the baffles have performed better at higher frequency with average attenuation being slightly higher in the filtered data.
Figure A-1. Trace balancing of the 50 mm baffle experiment data. Grayscale plots of channels 7–12 are shown (a) before and (b) after trace balancing. A normal moveout correction using an average tube-wave velocity of 1390 m/s was applied to each field file identifier (FFID) to flatten the strong coherent fluid-top tube-wave event (red) at 150 ms. The raw amplitudes of this horizon are picked/plotted (blue), and then summed and averaged. The inverse average amplitude is then used to normalize the field record. The same channel selection and horizon amplitudes are shown in the lower panel after ensemble balancing.

Figure A-2. (a) Raw and (b) amplitude-normalized data for the 100 mm baffle experiments. Data are normalized in a similar fashion to the 50 mm data, using first-break amplitudes from channels 8 to 12 prestacked field records. The additional weight of the 50 mm baffles (suspended below the analysis window) has induced cable waves in the SM and DM data. Additional mounting (DM) has only partially suppressed the induced cable waves.
Figure B-1. Tube-wave attenuation results for unfiltered and Butterworth frequency-filtered (25–150 Hz 12 dB/octave high and low cut) 50 mm corrugated pipe baffle experiments.
Figure B-2. Tube-wave attenuation results for unfiltered and Butterworth frequency-filtered (25–150 Hz 12 dB/octave high and low cut) 100 mm corrugated pipe baffle experiments.
Figure B-3. Power frequency spectrums for the unfiltered 50 mm baffle field experiments displayed from top to bottom as experimental data, power spectrum per trace overlapped with each other, individual power spectrum per depth/trace, and the spectrograph of the trace at 220 m depth for each baffle experiment.
Figure B-4. Power frequency spectrums for the Butterworth filtered (25–150 Hz 12 dB/octave high and low cut) 50 mm baffle field experiments displayed from top to bottom as filtered experimental data, power spectrum per trace overlapped with each other, individual power spectrum per depth/trace, and the spectrograph of the trace at 225 m depth for each baffle experiment.
REFERENCES


