Acquisition trial of deep smart DAS uphole: evaluating high-productivity drilling with dual rotary and fiber cable deployment

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Summary

The volume of seismic uphole surveys in the desert environment diminished, facing harsh drilling conditions and challenging acquisition. This occurs against a backdrop of the growing popularity of land depth imaging from the surface, demanding ever more accurate near-surface velocity calibration. We propose and field-test significant improvements in drilling and recording, leading to the next generation of smart DAS uphole surveys. First, we introduce dual rotary drilling to address unconsolidated sediments, karsts, and lost-circulation zones. This technique delivers 5-10 times productivity improvements compared to conventional rotary drilling. In addition, dual rotary enables deep 300 m upholes that were not previously achievable. We also upgrade fiber installation and cementation procedures leveraging the outer drill string/casing as protective media during cable installation. We present an integrated field trial of this new smart DAS uphole acquisition, drilling a 300 m uphole in under 12 operational hours and completing an uphole survey using DAS fiber-optic sensing technology in a fraction of the time required for conventional geophone uphole surveying.

Introduction

Uphole surveying is critical for building and calibrating near-surface velocity models. Imaging low-relief structures in the presence of complex near surface demands accurate calibration of statics to uphole data (Bakulin et al., 2017). Even more stringent requirements are imposed by depth imaging from topography. While such an approach is appealing and growing in popularity, indirect methods used for complex near surface such as seismic tomography and FWI possess significant uncertainty (Egorov et el., 2020). In essence, this is a depth conversion problem replicated on a smaller scale of the near surface. As in conventional depth conversion (Francis, 2018), borehole data plays a central role in reducing and mitigating velocity uncertainty associated with the seismic velocity. Therefore, the role of upholes is expected to increase with further progression of depth imaging workflows on land.

However, in terms of drilling and recording practices and accuracy, uphole acquisition remains almost the same as 60-80 years ago. Single-geophone tool is lowered into the well with often imprecise depth control. The operation is costly, with high drilling risk in shallow formations that suffer from unconsolidated collapsing sediments, lost-circulation, or significant karstification. Bakulin et al. (2017) introduced the concept of on-demand Smart DAS; when the cable is pre-installed in shallow holes and a survey is acquired with a single shot, reducing the risks and upgrading to multi-channel recording from surface to the total depth of the hole. In addition, fibers from multiple upholes can be connected to allow interrogating them with a single recorder to achieve fast and high-resolution uphole surveying and imaging with vertical arrays (Bakulin et al., 2017).

Smart DAS upholes enabled safer and more efficient acquisition (Bakulin et al., 2017). However, the challenge with drilling was not addressed. In addition, the fiber cable installation procedure was not optimized. In this study, we introduce and validate several significant improvements in the acquisition and operation of smart DAS uphole to achieve high-productivity operation and better quality DAS data.

Key challenges

During previous acquisition campaigns of geophone upholes and trials of smart DAS uphole in Saudi Arabia (Bakulin et al., 2017), the following main challenges were identified:

- Drilling risk and productivity in a karst environment with multiple lost-circulation zones was a major challenge. As a result, deepest upholes rarely exceeded 150 m;
- Hole stability was the second major concern. For geophone surveys, hole collapse often led to the loss of a geophone package triggering redrill. Also, for geophone and DAS sensors, hole collapse often prevented sensing package from reaching the total drilled depth limiting depth of investigation;
- Installation and coupling of DAS cables in shallow holes need to become less risky and more robust.

These challenges resulted in a lack of defined productivity, making it hard to plan time and budget for uphole acquisition. Based on these learnings, major enhancements were identified:

1) Dual rotary was identified as a primary improvement to reduce risk and increase drilling productivity;
2) The second improvement was protected fiber deployment attached to the outside of the grouting pipe and cementing in place.

This study describes field trial results validating and assessing these major improvements.

Dual rotary technology for high-productivity drilling

We identified dual rotary as a critical technology to solve the productivity of uphole acquisition in the presence of a complex near surface with loose sediments, karsts, and lost-circulation zones. Dual rotary means drilling is done using both outer drill casing and inner drill string (Figure 1). The inner drill string is typically equipped with a percussion hammer attached with a carbide button bit and the outer drill string is fitted with a carbide button studded shoe. When encountering unconsolidated sediments, karsts, or lost-circulation zones, the casing is advanced ahead of the drilling bit (Figure 1b). During conventional rotary drilling, there is no containment of unconsolidated geology or loss-circulation zones. In contrast, with dual rotary, these drawbacks are avoided and circulation is maintained in the annulus between the drill casing and inner drill string.

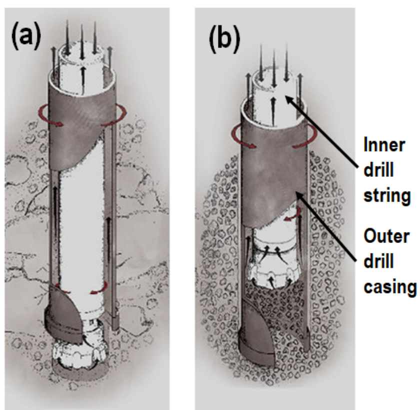

Figure 1: Dual rotary provides necessary edge to handle complex near surface: (a) in consolidated formations (normal drilling) – bit advanced, with or just ahead of the casing shoe; (b) in unconsolidated formations or karsts casing is advanced ahead of the drilling bit. This allows continued drilling while maintaining circulation.

The outer casing shoe protects the casing while advancing down the well. This only acts as a drill bit when in unconsolidated formation, and it is in advance of the inner string. The outer drill string is not used in consolidated and hard formations as the lead pipe.

Dual rotary was successfully applied in many other applications but, to our knowledge, was not used in the seismic industry before.

Fiber cable installation and cementation procedure

In initial trials, fiber cable attached to a carrier cable with the weight bar was deployed after pulling out the hole. Then hole backfilled through small tubing raised from the bottom of the hole. The deeper part of the holes sometimes collapsed. Fiber can be bunched when encountering obstructions downhole. Backfill with sand proved challenging to execute, especially in shallow parts, resulting in suboptimal data quality in the shallowest near surface (Bakulin et., 2017). Dual rotary lead to significant re-design of the entire deployment procedure:

- The casing of the dual rotary is kept for any necessary depth covering problematic drilling zones. Upon encountering consolidated formations without lost-circulation zones, the casing can be stopped in place while conventional rotary drilling continues with the inner drill string (Figure 2a);
- Upon reaching total depth, only the inner drill string is pulled out, while the outer drill casing is left in place to protect the problematic areas of the borehole;
- Grouting pipe or tubing is lowered down into the hole (protected by casing) with DAS cable clamped on the outside (Figure 2b);
- When the grouting pipe with DAS cables reaches TD, cementation begins by pumping cement through the grouting pipe. Cement travels up the annulus (between the grouting pipe and the open hole) until it reaches the surface. While cementing, the outer drill casing is gradually pulled out of the hole. At this point, even if the hole starts collapsing, the DAS cable is already installed and remains coupled in place with little risk;
- The final product is a smart DAS uphole with the fiber and grouting pipe (or tubing) cemented in place (Figure 2c). Cement provides an excellent bond between the fiber and the formation. The inside of the tubing is also covered with cement.

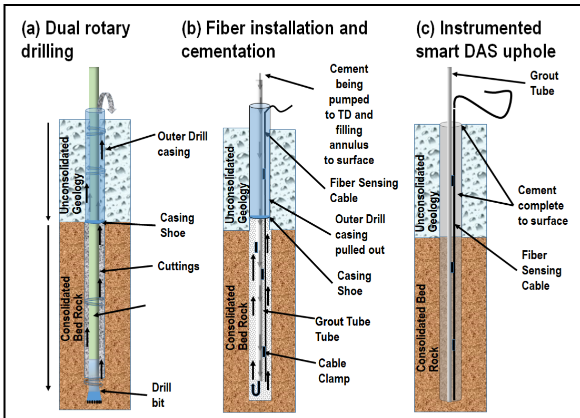

Figure 2: Schematic depiction of drilling, fiber installation, and cementation procedures: (a) hole drilled with dual rotary (casing stopped inside competent formation); (b) grouting pipe with clamped DAS cable on the outside is safely lowered inside the protective casing and cement is pumped to total depth and filling the annulus to the surface. At the same time, the outer drill casing is pulled out of the hole. (c) Final instrumented smart DAS uphole with the fiber cable cemented in place.

Tight placement of the outer drill string (casing) and unconsolidated nature of shallow sediments suggested that perhaps sufficient bond may be achieved for the uphole survey while casing remains in place. Indeed, Hardage (2000) indicated it may be entirely possible even for deeper wells. If this would be the case – this could allow leaving the casing permanently in place, simplifying the procedure. However, current limited surveying results shortly after drilling suggested that no sufficient mechanical bond has developed between casing and formation, leading to unacceptable quality of both DAS and geophone data, despite cementation of the annulus (between the tubing and outer casing). This explains the final step of pulling out the outer drill string when the fiber is safely in place. Alternatively, the shallow casing can be cemented to provide an excellent bond for geophone and DAS surveying, however, it increases the time and cost of the operation and was deemed unnecessary for this application.

Field trial and lessons learned

The initial trial was conducted in North America close to the drilling equipment origin to minimize cost. In addition, the trial location possessed highly unconsolidated sediments that replicate to some extent challenges of the desert environment with sand and loose deposits. Figure 3a shows the portable dual rotary rig and the support truck carrying drill pipes used during the trial. Figure 3b highlights two separate hydraulically-driven drives delivering dual rotary capability. The inner drill string is driven by a hydraulic top drive. The lower hydraulic drive rotates the casing pipe by the use of clamping jaws on the outside of the casing.

Dual rotary drilling was carried down to a depth of 65 meters (~ 210 ft) where competent bedrock was encountered. We then drilled using the inner drill string only down to 300 meters (~ 985 ft). The percussion hammer was used on the inner string for optimal drilling performance through consolidated hard formations (Figure 3c). Without a hammer, consolidated formations require a lot of hold-down weight thus making it very hard on the drilling rig. Drilling with a hammer requires very little hold-down weight and significantly increases penetration rate in hard formations while preserving the equipment.

The dual rotary drill presents little to no environmental impact, drilling with air circulation, using very small amounts of water mainly for dust control, and using small amounts of recycled vegetable oil from the food industry to lubricate the percussion hammer. We emphasize, that no chemicals were used in the process, thus ensuring no cross-contamination between any aquifers.

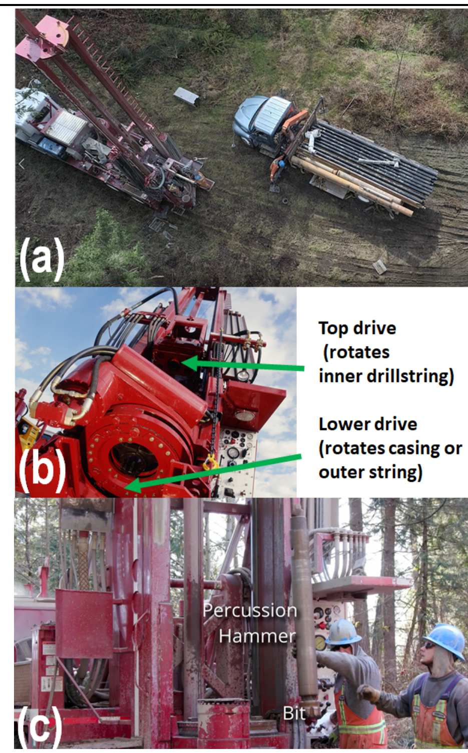

Figure 3: Dual rotary rig: (a) drone view of the rig during the field trial; (b) two drives independently rotate inner and outer drill strings; (c) the downhole percussion hammer is placed above the bit on the inner drill string to increase the penetration rate.

A deep smart DAS uphole of 300 meters was efficiently completed in under 12 hours of drilling time due to usage of dual rotary rig immune to lost-circulation zones and shallow sediment collapse. Contrast it with the conventional single rotary delivering 80-150 m hole in 3-7 days without guaranteed productivity. The trial has proven that dual rotary delivered three major improvements:

- Significant risk reduction in handling shallow sediments, lost-circulation zones, and karsts;
- A major 5-10 times gain in drilling productivity;
- Unlocking drilling of deep 300 m upholes, that were out of reach previously.

In collapsing sediments, a conventional geophone uphole survey can only be conducted inside the casing. This was tried and resulted in data with quality not acceptable for reliable picking of first breaks suggesting a poor bond between casing and formation (Hardage, 2000). Other studies noted that better seismic bonding to the formation could emerge as a well is aging, since drilling mud, rock cuttings, and sloughing better fill the annulus between the casing and the formation tends to solidify (Hardage, 2000; Goetz, 2013). The current trial only included short-term measurements (~ day), so perhaps further testing could be warranted to evaluate bond evolution with elapsed time. While not relevant to geophone surveys that need to be conducted immediately, smart DAS uphole could be pre-drilled and instrumented ahead of time, whereas recording could be done some days or weeks later, providing flexibility not available with geophone surveys.

Figure 4 illustrates the fiber-cable attachment procedure. First, cables are clamped on the outside of the grouting pipe using special clamps designed to provide firm attachment without damaging the cable. Next, sections of grouting pipe are added, fiber cables are clamped, and assembly is lowered down inside the protective casing. The last step is cementation in place along with the removal of the outer drill casing, finalizing the smart DAS uphole instrumentation sequence.

Figure 4: Fiber cable is attached with clamps to the outside of the grouting pipe before lowering to the hole. Grouting pipe is represented by PVC tubing.

DAS data assessment

DAS data quality is primarily controlled by the degree of mechanical coupling (Goetz, 2013; Daley et al., 2013; Reinsch, 2015). Provided outer casing is pulled out and grouting pipe cemented in place, excellent quality is achieved. Figure 5 shows examples of the field data recorded with cemented DAS cable using a weight-drop source. Consistent waveforms are observed both shallow and deep with easily pickable arrival times. Some waveform changes are observed on the shallowest traces due to the near-field effect and offset source. Finite-difference simulation with proper DAS gauge length and directivity modeling reveals similar waveform complications (Alfataierge et al., 2021). We conclude that shallow cementation of fiber delivers good data quality with stable waveforms suitable for uphole surveying and more advanced applications discussed below.

Conclusions

Large risk, challenging productivity, and higher cost have plagued seismic uphole acquisition leading to decreased usage. However, the growing popularity of land depth imaging and escalating accuracy requirements for depth conversion in the case of the low-relief structures demand upholes for building and calibrating velocity depth models for the near surface. Uphole information can significantly cut exploration and delineation risk by reducing the amount of dry and unnecessary deep wells. In addition, upholes substantially lessen turnaround time for velocity model building and imaging.

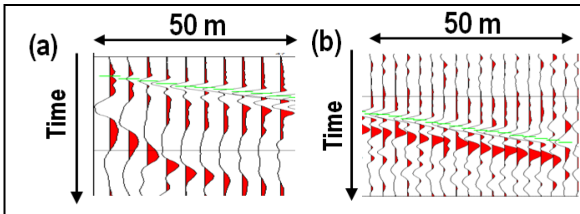

Figure 5: DAS data recorded with the weight drop source in different parts of deep smart DAS uphole: (a) shallow portion close to the surface; (b) deep portion close to a total depth of 300 m.

This trial tested a dual rotary technique typically used in other applications but not in the seismic industry. Drilling results exceeded our expectations and confirmed that the challenges above could be successfully addressed. In addition, we proved that deep 300 m holes could become a new norm. We believe this drilling technology will solve a 60 plus-year-old problem of efficient seismic uphole acquisition. In addition, the dual rotary has little to no environmental compact compared to conventional rotary drilling. We have further shown that dual rotary allows significant improvement in fiber installation and cementation procedures when acquiring smart DAS upholes. Specifically, fiber cables strapped to the outside of the grouting pipe could be lowered inside the protective outer casing, substantially cutting the risk of hole collapse. Fiber cable is cemented to the surface while the shallow outer drill casing is removed. On-demand smart DAS upholes can be pre-drilled and instrumented with fiber. The dedicated near-surface crew could acquire on-demand smart DAS upholes at critical prospects suffering from increased near-surface uncertainty. The DAS survey delivers densely sampled (~1-2 m) reliable waveforms from surface to total depth with a single shot. Compared to geophone surveys, acquisition time is cut from several hours to several minutes. Smart DAS uphole opens the opportunity to acquire walkaway and walkaround shot lines or 2D source carpets around the uphole. Smart DAS upholes can also be simultaneously recorded during surface seismic acquisition and used for near-surface and deeper imaging. Multi-shot uphole surveys may enable measuring of near-surface polar and azimuthal anisotropy as well as characterizing the distribution of small- and medium-scale near-surface heterogeneities that could allow decluttering seismic response. Such extended surveys are not achievable with geophone acquisition but could be particularly helpful in a complex desert environment where near-surface scattering plays a major role in obscuring surface seismic data and images.

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