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Assessment of rock-bit interaction and drilling performance using elastic waves propagated by the drilling system

Yingjian Xiao[a,*], Charles Hurich[b], Stephen D. Butt[a]

[a] Faculty of Engineering and Applied Science, Memorial University of Newfoundland, 230 Elizabeth Ave, St. John's, NL, Canada A1B 3X9

[b] Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada

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ABSTRACT

A novel passive Vibration Assisted Rotary Drilling (pVARD) tool was designed and tested to improve drilling performance or rate of penetration (ROP) both in laboratory and field trials. This paper focuses on characterizing drilling performance by means of seismic while drilling (SWD) method and bit vibration analysis. The field scale pVARD tool was applied in drill-off test (DOT) with an array of geophones (1C) spread along drill site. Rotary drilling using a polycrystalline diamond compact (PDC) bit was conducted and bit-rock interaction acted as the seismic source for reverse vertical seismic profile (RVSP). The rig waves were selected for characterizing drilling performance due to limited body waves observed during the experiment. The frequency spectra of the rig waves were determined which provided two effective seismic parameters: rig wave amplitude and frequency bandwidth for drilling performance analysis. These spectrums varied in response to variation in drilling conditions, i.e. weight-on-bit (WOB), pVARD tool use and configuration, and rock type. Bit vibration was assessed by means of vibration accelerations measured with a downhole SensorSub. The whole available data used for characterizing drilling performance included WOB, bit vibration accelerations, seismic wave amplitude and frequency bandwidth and rock type. Three groups of DOT tests were conducted: 1) conventional drilling in red shale, 2) pVARD drilling and conventional drilling in red shale, and 3) pVARD drilling and conventional drilling in grey shale. Analysis of the data shows that the seismic wave amplitude and frequency bandwidth decreased with increase of drilling performance. This is explained as more energy being partitioned for improved drilling performance with less energy partitioned to longitudinal wave and rig-ground motion. This phenomenon existed for both conventional drilling and pVARD tool drilling, independent of rock type. For comparable WOB, seismic wave amplitude and frequency bandwidth varied in response to drilling with or without pVARD tool, from which the pVARD tool mechanism was further investigated.

1. Introduction

A novel drilling tool, the passive Vibration Assisted Rotary Drilling (pVARD) tool, was designed and fabricated at Memorial University of Newfoundland, Canada. Field tests of this tool showed significant increase in rate of penetration (ROP).[1] However, the relationship between the enhancement mechanism of drilling performance and bit-rock interaction is the subject of ongoing research. The goal of this paper is to characterize drilling performance and bit-rock interaction using seismic while drilling (SWD) as one component of this ongoing work.[2] SWD is a passive seismic recording method using the interaction of the drill-bit and the formation to generate seismic waves that are recorded by surface geophones. Drill-off tests (DOT) are drilling experiments where drilling parameters are systematically varied and the impact on ROP is measured. Varied parameters for the DOTs in this investigation include weight-on-bit (WOB), rotary speed, rock type (i.e. stronger red shale and softer grey shale) and use of and configuration of the pVARD tool. This paper discusses two DOTs in red shale and 1 DOT in grey shale, both comparing conventional drilling and pVARD drilling. Comprehensive assessment is based on drilling data, seismic data, and bit vibration data recorded using a downhole SensorSub.

Improving ROP has been of paramount interest for drilling communities in oil and gas industry and technologies have been developed for achieving this target over the last century. Of all the technologies, utilization of natural bit vibration or addition of extra bit vibration on drill bit is one of the most effective and widely used. In 1902, rotary-percussion drilling was first proposed by adding percussive blows to the conventional rotary drilling as a means to improve ROP.[3] Since then, rotary-percussion drilling has evolved into one of the most efficient drilling methods using both top-hammer and down-the-hole hammer

* Corresponding author.
E-mail address: yxiao@mun.ca (Y. Xiao).

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configuration, in particular, for rapidly penetrating hard igneous and metamorphic rocks in the mining and construction industries. In the 1950s, resonant sonic technology was developed which applies sub-percussive axial vibrations to the bit to successfully increase bit cutting efficiency and improve drilling performance.[4] This technology has evolved into sonic drilling, which is widely used for rapid drilling in soils and similar unconsolidated materials. However, for various reasons, neither drilling technology is suited for oil and gas drilling in sedimentary formations where well control must be maintained to prevent kicks and blowouts. At the Drilling Technology Laboratory of Memorial University of Newfoundland, a group of drilling engineers investigated the possibilities of using natural bit vibration to improving drilling performance for otherwise conventional rotary drilling. By drilling with a polycrystalline diamond compact (PDC) bit and adding dampening elements beneath rock specimens in combination to a pulse cavitation drilling tool, the dampening compliance enhanced the oscillatory bit-rock interaction and resulted in improved cutting efficiency and overall drilling ROP.[5] After this, the idea was further developed by incorporating the dampening elements directly into the drill string which also improved drilling ROP. These concepts were progressively investigated and refined and incorporated in both laboratory and field scale versions of the pVARD tool, which demonstrated improved ROP under both laboratory and field conditions.[6,7] A set of pVARD field trials formed the basis of the investigation reported in this paper.

Drilling performance is strongly influenced by bit motions and bit-rock interaction which has extensively studied on widely used bits such as roller cone and PDC bits. Theoretical models have been developed to assess forces applied in roller cone bits and the correlation to ROP and drilling conditions [e.g. [8,9]] Empirical relations were proposed to correlate drag forces on a single-cutter PDC bit to rock type, depth-of-cut (DOC) and bit wear state [e.g.[10]]. Some researchers have reported on bit-rock interactions through measurement and evaluation of the three modes of drill string vibrations (i.e. axial, lateral and torsional) recognizing that these drill string vibrations are excited by bit-rock interactions.[2,11,12] For example, a numerical study of coupled axial and torsional vibrations showed the root cause of self-excited vibration as the delay in axial position of the bit, during the drag bit-rock interaction.[13] These bit vibrations were experimentally measured as accelerations with a down-hole SensorSub,[14] and the acceleration data interpretation were used to correlate bit vibrations to drilling conditions such as rock type and WOB.[15] In the laboratory tests, axial bit vibration generated from the pVARD tool was recorded by a laser probe, showing the vibration played a great role in improving drilling performance,[6,7] and frequency peaks of axial bit vibrations were found around the angular velocity and its multiples.[12]

Seismic while drilling was intensively studied during the 1980s and 1990s.[16] This technology had many applications such as positioning the drill-bit, real-drill-time imaging ahead of bit, guiding the bit to a target, predicting overpressure intervals ahead of bit. Of all the applications, characterization of bit rock interaction and drilling performance using SWD method was of greatest interest in the current discussion: spectral content analysis of a radiated source is a frequently used method which helps to better understand drill bit conditions. For example, from accelerometers attached to the rig recording roller cone bit drilling source, frequency peaks showed the relationship to formation characteristics[17] and bit wear state.[18] Frequency peaks of the seismic sources showed the relation to bit geometries of both coring bit and roller cone bit.[19] Frequency spectrums from rotary-percussion drilling sources showed relationship between specific band to drilling conditions,[20] bit types[21] and rock type.[22]

2. Methodology

2.1. The pVARD technology

The pVARD tool consists of an inner hollow shaft and an outer shell, between which relative motions occur. A group of springs and dampening rubbers included in the inner shaft absorb and convert natural bit vibrations to axial displacement. This pVARD technology, incorporating spring compliance into the drill string, improves bit-rock interaction and increases ROP. This tool passively employs natural bit vibration and shows promising improvement in drilling performance from laboratory and field tests.[6]

In this paper, the setting of pVARD tool was set as 'V12000' which showed a 25% compression of stacked springs under the load of 12,000 pounds from a laboratory loading test.[1]

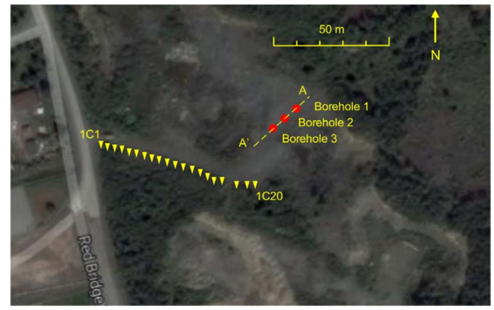

Fig. 1. Spread of 1C geophones array (20) with three seismic source boreholes in Greenslades Construction Quarry of east Newfoundland (based on Google map).

2.2. Experimental methods

Three shallow boreholes were drilled in September 2014 for testing the pVARD tool protocol at Greenslades Construction Quarry of eastern Newfoundland and Labrador, Canada. Fig. 1 shows the geometry of boreholes and an array of 1C geophones (20) which are in-line spread. The space between geophones is 5 m. Three boreholes were drilled with an offset of approximately 7 m. The data were recorded using single, 14 Hz, vertical component geophones at each recoding site. High quality geophone coupling was accomplished by setting the geophones in exposed bedrock by drilling a small hole to accommodate the geophone spike. The data were recorded with an ARAM Aries distributed recording system mirrored to a quality control computer and preliminary test processing was carried out in the field to monitor record quality and noise. Each record was recorded for 30 s. A number of noise records with the rig running but not drilling were recorded to establish background and rig noise levels.

The lithology of underground formations by cross section A-A′ is shown in Fig. 2. The lithologic section is composed of the Manuels River Formation of the Harcourt Group which is black to dark grey shale with thin beds of grey limestone which is labelled as grey shale in this investigation. This formation is underlain by the Chamberlain's Brook Formation of the Adeyton Group defined as green to grey shales with some red mudstones and shales, and is labelled as red shale.[23] This lithology cross section was confirmed by analysing drill cuttings circulated back to surface.

SWD recording took place during the drilling tests to evaluate if SWD data could be used to characterize rotary drilling performance. The drill rig used was an Ingersoll Rand T3W rig (Fig. 3). The pVARD tool was installed above the downhole sensorSub which was used to measure bit rotations and multi-axis accelerations. A rotary-percussion hammer bit was used to penetrate the upper formations to the trial depths, followed by drilling using PDC and roller cone bits and with and without the pVARD tool. In this paper, the 152 mm PDC bit was used as the only bit for investigating drilling performance. A linear array of geophones at the surface was deployed as is typical in the reverse vertical seismic profile (RVSP) method.

Drilling parameters were obtained from the drill rig, i.e. WOB, rotary speed, drilling depth and duration. Those parameters remained constant for each three meters drilling interval. The drilling rotary