



# Application of laboratory-based rate of penetration model for polycrystalline diamond compact bit to geothermal well drilling

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**Abstract** The modeling of the rate of penetration (ROP) considering the degradation of drilling performance owing to bit wear is essential for planning efficient and economical drilling. In the present study, a laboratory-based ROP model for a polycrystalline diamond compact (PDC) bit is reviewed and the applicability of the model to the field data obtained in the four drilling tests performed by drilling structural boring wells in geothermal regions is investigated. It is validated that, on the whole, a parameter representing bit performance exponentially decreased with drilled length, suggesting that the decrease in ROP owing to bit wear is appropriately considered by the model, except when inherent performance of a PDC bit is not sufficiently exerted for some reason, e.g., inefficient transport of cuttings. The findings of the present study are expected to contribute to the optimization of drilling plans, including appropriate bit selection and bit life estimation.

## Article highlights

- The laboratory-based ROP model for PDC bit was reviewed and differentiated from other models.
- The field drilling data of bit performance were found to be explained satisfactorily by the ROP model.
- ROP decreased exponentially with drilled length during the drilling of hard formations for PDC bits.

**Keywords** Polycrystalline diamond compact · Drilling test · Rate of penetration · Bit wear · Rock abrasivity

## 1 Introduction

The use of polycrystalline diamond compact (PDC) bits has rapidly spread in oil and gas well drilling, replacing conventional roller-cone bits. It has been reported that PDC bits (including diamond bits) account for an astounding 65% of the total footage drilled in oil and gas applications in 2010 and still do not appear to have peaked in their development (Bellin et al. 2010). Recently, PDC bits have begun to be used in other industrial fields, e.g., geothermal well drilling and coal mining. In particular, a growing number of case studies in the geothermal field have been reported (Finger and Blankenship 2010;

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Raymond et al. 2012; Sabri et al. 2016; Gunawan et al. 2018; Imaizumi et al. 2019).

Modeling of the rate of penetration (ROP) is essential to prepare an optimized drilling plan depending on the drilling scenarios and conditions. The arrangement of ROP models for a variety of bits contributes to bit selection in accordance with the geological information of the rock formation to be drilled. Reliable ROP models in which the decrease in ROP owing to bit wear is appropriately taken into consideration are required to be developed to estimate bit life and the time to replace the bit in use with a new one. The estimation of bit life is also essential to planning well drilling, because enormous time and cost are consumed in bit replacement, especially in deep drilling.

Although many ROP models for PDC bits have been proposed, very few models consider the effect of bit wear (Hareland and Rampersad 1994; Motahhari et al. 2010; Soares et al. 2016; Mazen et al. 2021; Miyazaki et al. 2022). Miyazaki et al. (2022) showed that ROP decreased exponentially with the wear volume of polycrystalline diamond (PCD) layers by a series of laboratory drilling tests using a PDC bit under controlled conditions and proposed an ROP model with an extremely simple form.

The quantitative estimation of the degradation of the drilling performance owing to bit wear is essential for planning efficient and economical drilling. In the present study, the applicability of the ROP model proposed by Miyazaki et al. (2022) to the field data obtained in drilling tests performed in geothermal regions is investigated. In particular, the applicability of a parameter representing bit performance, which can be obtained simply from drilling parameters and rock properties, was verified. The findings of the present study are expected to contribute to the optimization of drilling plans, including appropriate bit selection and bit life estimation.

## 2 ROP model

### 2.1 ROP model proposed by Miyazaki et al. (2022)

Miyazaki et al. (2022) showed by a series of laboratory drilling tests that ROP decreased exponentially with the wear volume of PCD layers after the appearance of bit wear and proposed an ROP model as a

function of rotary speed, weight on the bit (WOB), rock strength, and wear volume of PCD layers:

$$u = p_0 \cdot N \cdot (W/S_c)^2 \cdot \exp(-\gamma \cdot V_{wd}), \quad (1)$$

where  $u$  is ROP,  $N$  is rotary speed,  $W$  is WOB,  $S_c$  is the uniaxial compressive strength (UCS) of drilled rock,  $V_{wd}$  is average wear volume of PCD layers on 16 cutters in the nose and shoulder portions of the bit, and  $p_0$  and  $\gamma$  are the parameters representing the bit performance when the bit starts to wear and the magnitude of the effect of  $V_{wd}$  on  $u$ , respectively. In the perfect-cleaning model proposed by Maurer (1962),  $u/N$  was assumed to be proportional to  $(W/S_c)^2$ . Miyazaki et al. (2022) showed that  $u/N$  is almost proportional to  $(W/S_c)^2$  even when the bit wear progresses, as suggested in Eq. (1). Bit performance  $p$  can be expressed as

$$p = \frac{u/N}{(W/S_c)^2} = p_0 \cdot \exp(-\gamma \cdot V_{wd}). \quad (2)$$

The ROP model was constructed on the basis of the results of laboratory drilling tests, in which five types of rock were successively drilled for 98 m in total by a PDC bit of 216 mm (8.5 inches) diameter shown in Fig. 1, using the drilling apparatus shown in Fig. 2. A total of 58 PDC cutters (50 on the face, 8 on the gage) with 13.44 mm diameter and 8 mm



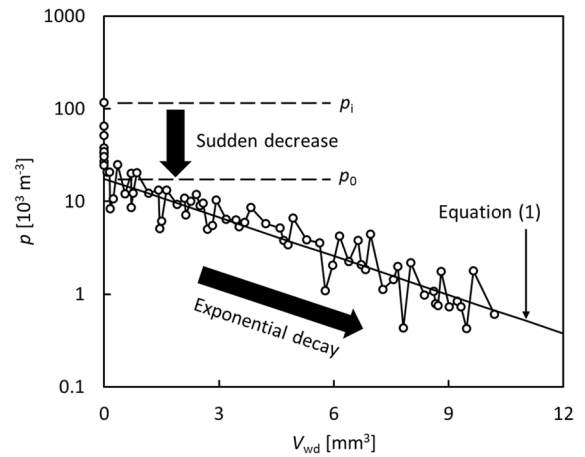
**Fig. 1** PDC bit



**Fig. 2** Drilling apparatus

thickness were attached to the bit body and 24 arrestors (3 on each blade) were mounted behind the PDC cutters in the nose and shoulder portions to suppress the impact on the PDC cutters during drilling. The thickness of the PCD layer is 1.6 mm. The back rake angle of every face cutter was 15°. The wear flat length of the 16 cutters (2 cutters on each blade) in the nose and shoulder portions of the bit, on which a relatively large wear flat was observed, was measured after every 1.4 m of drilling. Assuming that a cutter is a cylinder and that the wear flat is formed into a cut surface of the cylinder as a plane, the wear volume of the PCD layer can be obtained mathematically from the measured wear flat length and geometry of the cutter. Refer to Miyazaki et al. (2022) for details of the test conditions and the calculation method of  $V_{wd}$ . Figure 3 shows the change in  $p$  in the test, calculated by Eq. (2). First,  $p$  suddenly decreased from its initial value  $p_i$  to  $p_0$  while  $V_{wd}=0$ , i.e., bit wear was not observed, although microscopic bit wear probably occurred. Second,  $p$  decreased exponentially (linearly on a semi-log plot) with  $V_{wd}$ . Equation (1) expresses the process of exponential decay of  $p$  after bit wear was observed, as shown in Fig. 3.

Miyazaki et al. (2022) also showed that  $V_{wd}$  increased linearly with the drilled length  $L_d$  after bit wear was observed and that the rate of increase in  $V_{wd}$  was closely related to indexes of rock abrasivity,



**Fig. 3** Change in  $p$  with  $V_{wd}$  in the laboratory drilling test (Miyazaki et al. 2022)

e.g., Schimazek’s F-abrasivity factor (Schimazek and Knatz 1970) and rock abrasivity index (Plinninger 2002), which are widely used in the fields of civil and mining engineering. As  $V_{wd}$  is proportional to  $L_d$  in the case of drilling a uniform rock formation, Eq. (2) can be rewritten as

$$p = p_0 \cdot \exp(-\gamma' \cdot L_d), \tag{3}$$

where  $\gamma'$  is a parameter representing bit durability during the drilling of the rock formation.

### 2.2 Earlier ROP models considering bit wear

Soares et al. (2016) adopted two ROP models that incorporate the effects of bit wear in examining the reproducibility of the field ROP data. One model is Hareland’s ROP model for PDC bits (Hareland and Rampersad 1994) with the addition of a parameter representing bit wear. The other model is Motahhari’s model (Motahhari et al. 2010), which is based on the results of cutting tests using a single cutter and employs theoretical considerations to account for interaction among neighboring cutters (Glowka 1987). The ROP model proposed by Miyazaki et al. (2022) is unique in that its expression has an extremely simple form compared with Hareland’s and Motahhari’s models in addition to being based on the results of laboratory drilling tests using a real-scale PDC bit under controlled conditions.

There have been several studies to investigate the correlation between bit wear and torque. Mazen et al. (2021) introduced a new wear index  $W_i$  to predict ROP:

$$W_i = W/d_c + 2\pi T/A_c, \quad (4)$$

where  $d_c$  is the depth of cut,  $T$  is torque, and  $A_c$  is the cutting area of a cutter. Karasawa et al. (2016) reported that the progress of bit wear can be qualitatively detected by measuring bit torque. However, it is difficult to measure bit torque accurately, because the torque measured at the drilling site actually includes torque owing to friction between the drill string and sidewall of the wellbore in most cases.

### 3 Field drilling test

#### 3.1 Field test conditions

Table 1 shows the test conditions of the four field tests performed by drilling structural boring wells in geothermal regions. The field tests and PDC bits used are hereafter referred to as Field tests No. 1 to No. 4 and Bits A, B, C, and D, respectively. Bits A and B have the same geometric design as the bit used in the laboratory tests of Miyazaki et al. (2022), whereas

Bits C and D have designs different from them. Bits C and D have 25 backup cutters to prevent the primary cutters from penetrating too deeply into the rock in place of 24 arrestors. The back rake angles of the face cutter of Bits C and D were 20° and 15°, respectively.

#### 3.2 Drilling performance before field tests

Laboratory drilling tests of the bits were performed before the field tests to assess their inherent drilling performance. As shown in Fig. 4a,  $u/N$  increased with  $W$  for each bit. For Bits A and B,  $u/N$  was approximately equal because they had the same geometric design. For Bits C and D,  $u/N$  was lower than that of Bits A and B, suggesting that the depth of cut of primary cutters was suppressed by the backup cutters. It is reasonable that  $u/N$  of Bit C was lower than that of Bit D, because the back rake angle of Bit C was larger than that of Bit D.

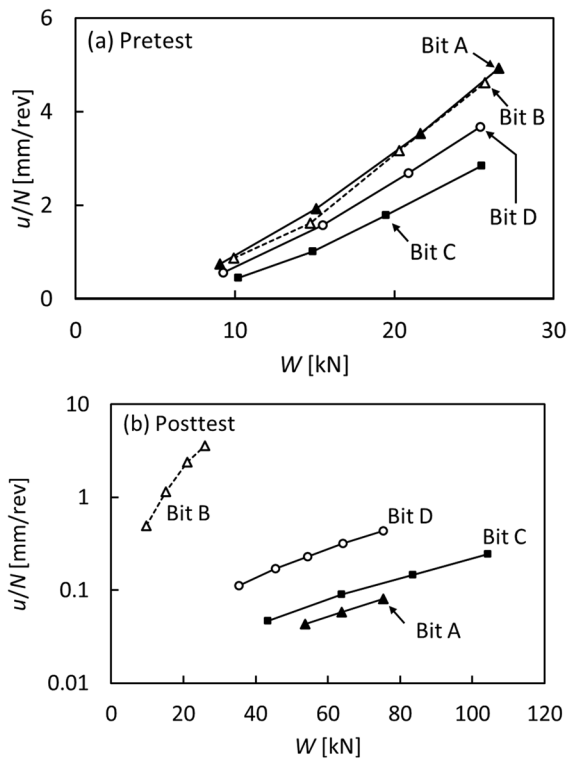
#### 3.3 Field tests

A brief outline of the field tests is described in Table 1. The IADC dull grades (Brandon et al. 1992) indicate the average volume of the cutters worn away in the field test for inner and outer rows (inner 2/3 and outer 1/3 of the bit diameter). Field tests No. 1, 3, and 4 were finished because Bits A, C, and D were judged

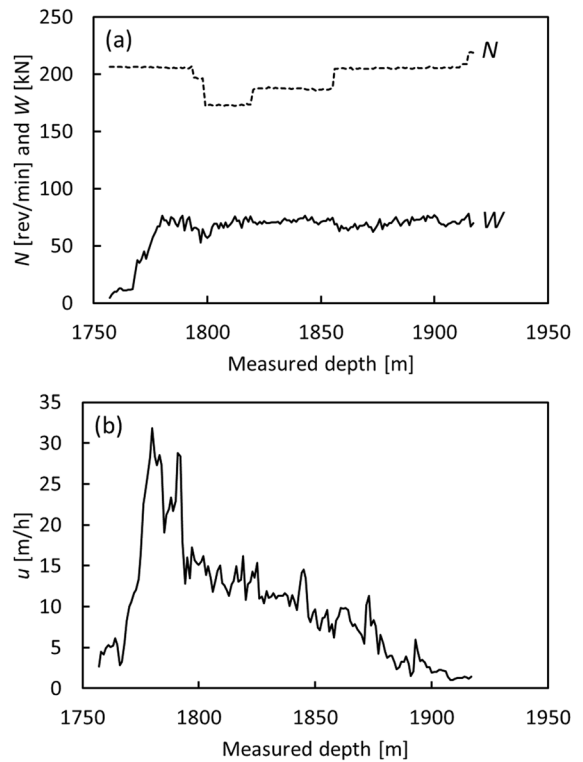
**Table 1** Summary of field tests, pretests, and posttests

Field test No.	1	2	3	4
<i>Conditions</i>				
Planned target section (8.5 inches hole)	1600–2000 m	870–1100 m	1200–1800 m	1200–1700 m
Geological formation	Late Miocene dacite tuff breccia and lapilli tuff (mostly welded) with breccia	Tuffaceous sandstone, lapilli tuff, and volcanic conglomerate	Neogene andesite lava and hornblende dacite pyroclastic rock (with basalt intrusive rock)	Quartz-rich andesite, dacite and basalt
Bit name	Bit A	Bit B	Bit C	Bit D
<i>Results</i>				
Actual drilled section (Measured depth)	1756–1917 m	797–1106 m	1210–1249 m (1st use) 1414–1484 m (2nd use)	1372–1392 m
Bit-run time	31.0 h	93.4 h	56.0 h	9.0 h
IADC dull grade Inner rows (In), Outer rows (Out)	In: 2, Out: 3	In: 0, Out: 1	In: 0, Out: 1 (1st use) In: 1, Out: 3 (2nd use)	In: 1, Out: 3
Bingham's $b^*$ Pretest/posttest	1.8/1.8	1.8/2.0	2.0/2.2	1.9/1.8

\* $b$  is Bingham's exponent (1964):  $u/N \propto W^b$



**Fig. 4** **a** Pretest and **b** posttest results of Bits A, B, C, and D



**Fig. 5** Changes in **a**  $N$ ,  $W$ , and **b**  $u$  in Field test No. 1 (Bit A)

to have reached the end of life; Field test No. 2 was finished because the planned total depth was reached. The changes in  $N$ ,  $W$ , and  $u$  with measured depth (MD) in Field tests No. 1–4 are shown in Figs. 5, 6, 7 and 8, respectively.

For Bit A, although  $u$  reached 30 m/h at MD=1780 m, it gradually decreased to 1.5 m/h, while  $W$  remained almost constant, during drilling through 161 m of rock formation consisting mainly of dacite tuff breccia.

For Bit B,  $u$  fluctuated irregularly between 1 and 30 m/h while drilling through 309 m of rock formation consisting mainly of tuffaceous sandstone.  $u$  is comparably low at MD=952–1018 m, where slide drilling was performed with the rotary of the drill string stopped. As the drilled rock was considered to be considerably soft, almost no wear was observed on Bit B after the field test.

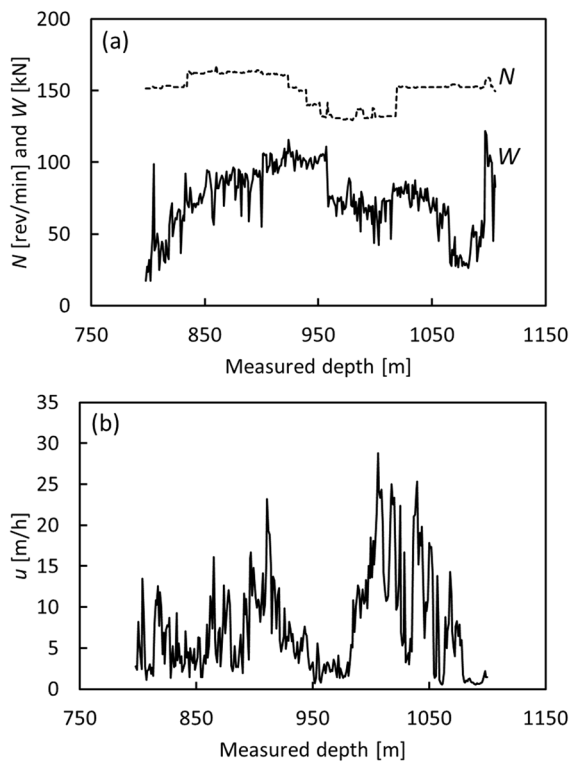
Bit C was used twice in Field test No.3. During the first use,  $u$  reached 8 m/h at MD=1238 m and then decreased below 1 m/h at MD=1249 m for unclear

reasons. As Bit C appeared to be still functional to drill the rock formation after the first use, it was used again after drilling with a roller cone bit. During the second use,  $u$  reached 5 m/h at MD=1420 m and then decreased below 1 m/h at MD=1484 m.  $u$  decreased suddenly at MD=1458 m, where it was presumed that hard intrusive basalt was encountered on the basis of the observation of rock cuttings.

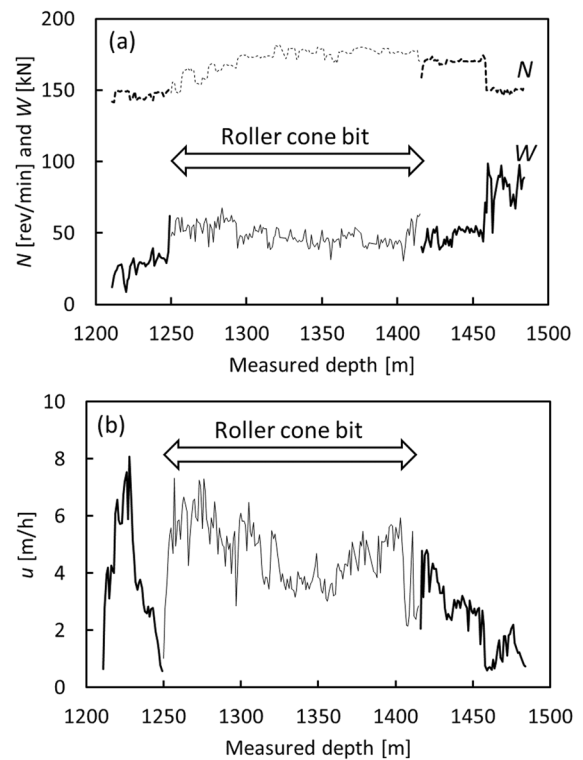
For Bit D,  $u$  changed with MD, as shown in Fig. 8, while drilling through 20 m of rock formation consisting mainly of quartz-rich andesite, dacite, and basalt.  $u$  decreased to 1.1 m/h at MD=1385 m, then temporarily increased owing to the increase in  $N$  and  $W$  at MD>1385 m. However, it soon decreased again to 1.6 m/h.

### 3.4 Drilling performance after field tests

After the field tests, the laboratory drilling tests of the bits were performed again. As shown in Fig. 4b,  $u/N$  of Bit B was extremely high compared with those of



**Fig. 6** Changes in **a**  $N$ ,  $W$ , and **b**  $u$  in Field test No. 2 (Bit B)



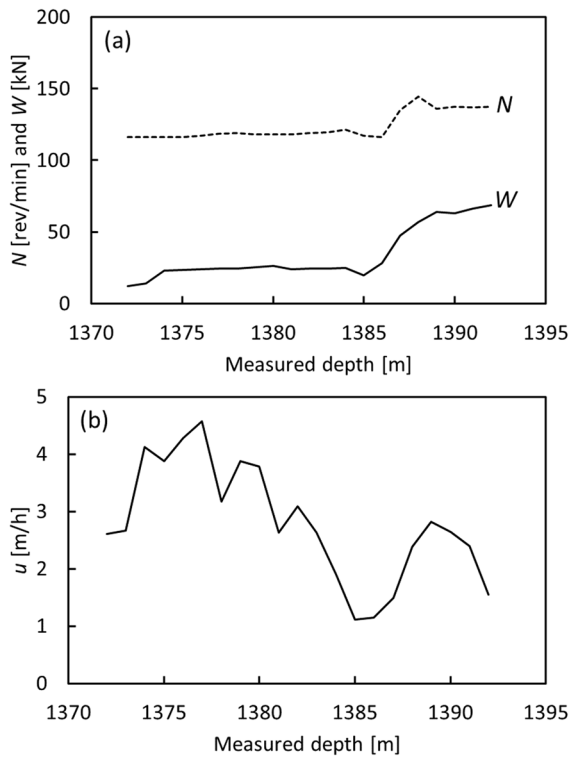
**Fig. 7** Changes in **a**  $N$ ,  $W$ , and **b**  $u$  in Field test No. 3 (Bit C)

A, C, and D, which is consistent with the IADC dull grade shown in Table 1: the bit wear and decrease in  $u/N$  owing to being subjected to the field test was much smaller for Bit B than for the other bits.

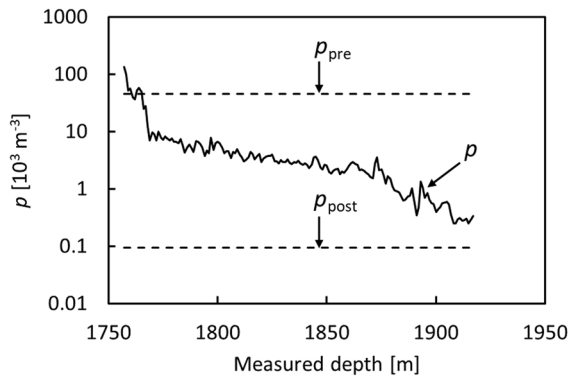
Hereafter, the laboratory tests before and after the field tests are referred to as pretests and posttests, respectively. Bingham (1964) mentioned an approximation in which  $u/N$  is proportional to the  $b$ th power of  $W$  on the basis of a large amount of drilling data and described that  $b$  ranges from 0.9 to 3.0 for most rocks and bits.  $b$  values obtained by the least-squares power approximation of the  $u/N$ – $W$  relationships in the pretests and posttests are shown in Table 1. Note that  $b$  is approximately equal to 2 in both the pretests and posttests. Assuming that Eq. (1) is applicable to the bits used in the field tests,  $p$  values in the pretests,  $p_{\text{pre}}$ , and posttests,  $p_{\text{post}}$ , can be calculated using  $S_c$  of the drilled rock samples and are to be compared with  $p$  in the field tests in the following section.

#### 4 Discussion

In Field test No. 1, it is inferred from the observation of rock cuttings that the rock formation drilled by Bit A was almost uniform.  $S_c$  was measured in the laboratory using the core samples recovered from MD=1753–1757 m, which is the section immediately above the section drilled by Bit A. The change in  $p$  in Field test No. 1 calculated by Eq. (2) using  $S_c$  measured in the laboratory and  $N$ ,  $W$ , and  $u$  measured at the field site is shown in Fig. 9. The initial and final values of  $p$  in the field test are almost consistent with  $p_{\text{pre}}$  and  $p_{\text{post}}$  obtained in the laboratory tests of Bit A, respectively.  $p$  decreased suddenly approximately from  $100 \times 10^3 \text{ m}^3$  to  $10 \times 10^3 \text{ m}^3$  at the beginning of the drilling and then continued to decrease gradually below  $1 \times 10^3 \text{ m}^3$ , as observed in the laboratory drilling tests and shown in Fig. 3. The approximate consistency among laboratory test results,



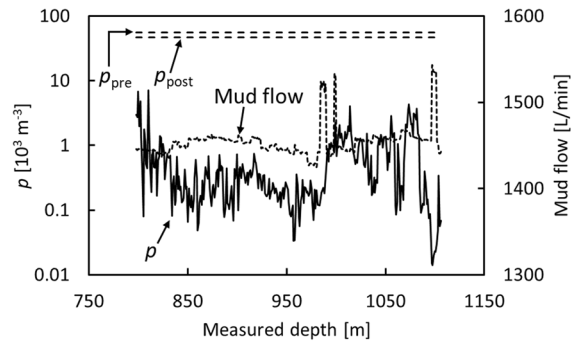
**Fig. 8** Changes in **a**  $N$ ,  $W$ , and **b**  $u$  in Field test No. 4 (Bit D)



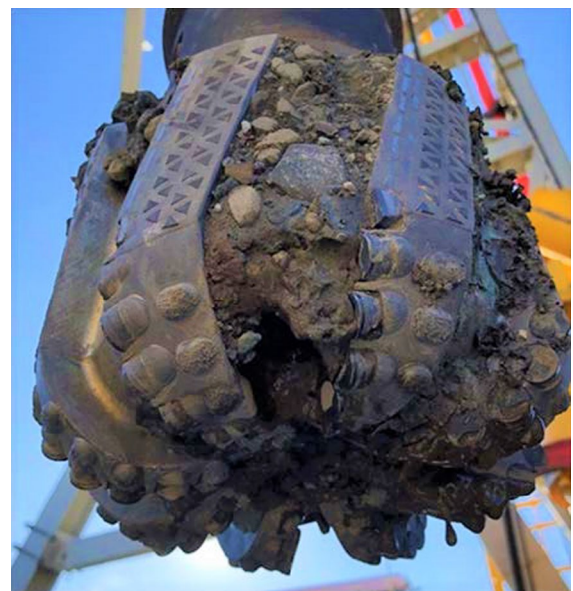
**Fig. 9** Change in  $p$  in Field test No. 1 (Bit A)

laboratory-based model results, and field data are considered to be of significance from the engineering perspective; a practical drilling plan may be prepared for field sites using the ROP model.

For Field tests No. 2 to No. 4,  $S_c$  was estimated by mechanical tests in the laboratory using the core samples recovered from a neighboring region. The changes in  $p$  in Field test No. 2 is shown in Fig. 10.



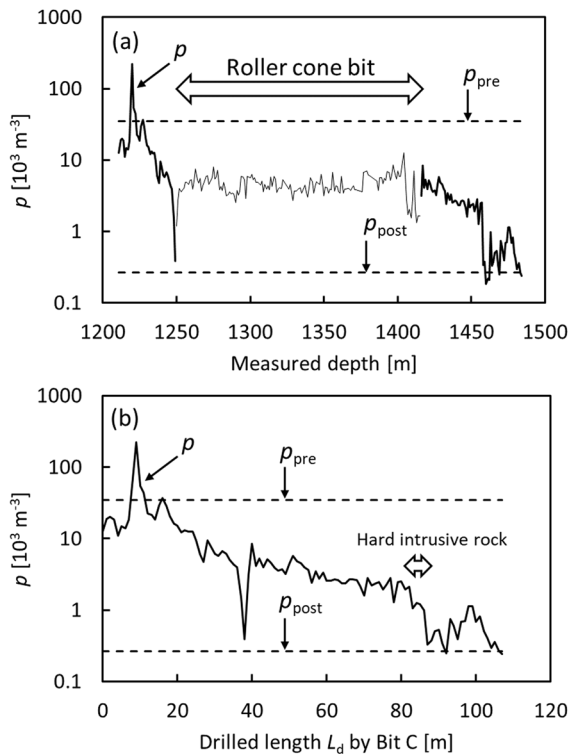
**Fig. 10** Change in  $p$  in Field test No. 2 (Bit B)



**Fig. 11** Bit balling of Bit B observed after the field test

$p$  was markedly lower than  $p_{pre}$  and  $p_{post}$ . In Field test No. 2, the rock formation drilled by Bit B was so soft and ductile that bit balling occurred during drilling; rock cuttings accumulated and stuck to the bit body, as shown in Fig. 11.  $p$  increased temporarily several times immediately after mud flow increased, as shown in Fig. 10, indicating that Bit B could not exert its inherent performance because of the inefficient transport of cuttings.

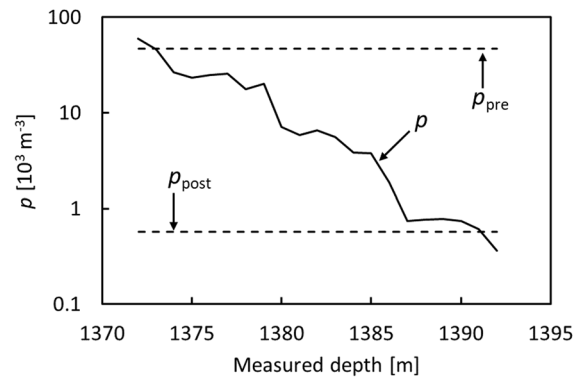
In Field test No. 3, hard intrusive basalt was encountered at MD from 1458 to 1462 m.  $S_c$  values for the basalt and the other formation mainly consisting of andesite and dacite were estimated to be



**Fig. 12** Change in  $p$  in Field test No. 3 (Bit C)

367 MPa and 153 MPa, respectively. Figure 12a shows the change in  $p$  in Field test No. 3. It was found that  $p$  for the roller cone bit was almost constant, although it is unclear whether the ROP model expressed by Eq. (1) is applicable to roller cone bits. Figure 12b shows  $p$  versus drilled length  $L_d$  by Bit C, excluding the section drilled by the roller cone bit in the interval between the first and second uses of Bit C.  $p$  gradually decreased with  $L_d$  until  $L_d$  of 80 m, except for the instant decrease at the end of the first use at  $L_d$  of 38 m. The slope of  $p$  appears to be steeper during the drilling of the hard intrusive basalt. Note that Eq. (3) is applicable to the case of drilling a uniform rock type. Thus, the change in the slope of  $p$  suggests that the abrasivity of the basalt is higher than that of the other formation drilled in the field test. Although  $p$  appeared to recover at around  $L_d$  of 98–99 m for some reason, e.g., overestimation of  $S_c$ , after drilling the intrusive basalt,  $p$  soon decreased and reached the final value almost corresponding to  $p_{\text{post}}$ .

The reason for the instant decrease in ROP and  $p$  at  $L_d$  of 38 m is unclear. The IADC dull grades for the first use of Bit C were 0 and 1 for inner and outer



**Fig. 13** Change in  $p$  in Field test No. 4 (Bit D)

rows, respectively, which means that the bit wear progressed very slightly during the first use. Although the presence of hard intrusive rock was suspected, the geological formation did not seem to vary at around  $L_d$  of 38 m, as judged on the basis of the observation of rock cuttings. In addition, adequate mud flow was maintained, and no particular drilling operation was conducted at around  $L_d$  of 38 m. Thus, we infer that the instant decrease in ROP and  $p$  was brought about by the insufficient transmission of thrust force, probably caused by unexpectedly high friction of drill strings owing to key seating, cuttings bed formation in the wellbore, and so on.

In Field test No. 4, the logarithm of  $p$  decreased linearly ( $p$  decreased exponentially) with MD, as shown in Fig. 13. The initial and final values of  $p$  approximately corresponded to  $p_{\text{pre}}$  and  $p_{\text{post}}$ , respectively.

The applicability of the laboratory-based ROP model proposed by Miyazaki et al. (2022) to field data of well drilling was examined referring to the results of Field tests No. 1 to No. 4. It was validated that, on the whole,  $\log p$  linearly decreased ( $p$  exponentially decreased) with  $L_d$  in the field tests, suggesting that the effect of bit wear on ROP is approximately expressed by Eq. (3), except in Field test No. 2 in which the inherent performance of Bit B was not sufficiently exerted because of the inefficient transport of cuttings. Overall, the laboratory-based ROP model is considered to be applicable to field data.

In this study, almost no quantitative information was available on the wear of the PDC bits used in the field tests except for the IADC dull grade. As described in 3.4, the  $u/N$ - $W$  relation or  $p_{\text{post}}$  is



considered to correlate with the degree of bit wear. It is necessary to acquire more detailed data on the actual degree of bit wear than the IADC dull grade in order to improve the reliability of  $p$  as an indicator of bit wear. Since  $p$  is simply calculated from drilling parameters ( $u$ ,  $N$ , and  $W$ ) and the rock property ( $S_c$ ) as expressed in Eq. (2), the degree of bit wear may be observed by monitoring  $p$  in real time at drilling sites. In addition, as  $p$  values measured in laboratory and field drilling tests were found to be comparable even without correction,  $p$  is considered to be obtainable with reasonable reliability in field drilling.

There are several points to which attention should be paid in applying the ROP model. Firstly, the ROP model is available only for the PDC bits of which  $u/N$  is approximately proportional to the square of  $W$ . Thus, when the ROP model is to be applied to field drilling data, it is recommended to obtain the exponent of the power approximation of the  $u/N$ – $W$  relationship in advance by laboratory drilling tests using the bit itself or a bit with the same specifications as those used in the field drilling. Secondly, the ROP model is currently applied to the drilling of comparably hard formations. It is unclear whether Eq. (1) is applicable to different types of formation, such as abrasive sedimentary rock. Although Field test No. 2 offered the only chance to examine this point, the inherent performance of Bit B could not be observed because of the inefficient transport of cuttings. As the abrasiveness of rock is an important factor affecting bit wear, it is necessary to verify the applicability of the ROP model to abrasive rock. Note also that the slope of  $\log p$ – $L_d$ , or  $\gamma'$  in Eq. (3), depends on the bit durability and rock abrasivity and is difficult to estimate appropriately prior to field drilling. A method of qualitatively predicting  $\gamma'$  is expected to be developed.

## 5 Conclusion

In the present study, the applicability of the ROP model, which was developed on the basis of the results of laboratory drilling tests (Miyazaki et al. 2022), to field drilling data in the geothermal region was examined. The field data of  $p$ – $L_d$  were found to be explained satisfactorily by the ROP model.

Several issues should be investigated in the future. The application range of the ROP model will be experimentally verified and expanded for different types, sizes, and designs of bits and for different types of rock. The formulation of ROP considering the effect of bit wear is expected to contribute to the planning of efficient and economical drilling, including appropriate bit selection and bit life estimation, in accordance with the well design, drilling equipment, and geological conditions. The findings in the present study are expected to lead to the promotion of the practical use of PDC bits for well drilling in various fields with greater economic efficiency.

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**Author contributions** KM mainly led the research and wrote the manuscript. TT prepared the figures concerning the laboratory data. MT prepared the figures concerning the field data.

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**Declarations**

**Competing interests** The authors have no competing interests.

**Ethical approval** This declaration is not applicable.

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