Theoretical analysis of the influence of drilling compaction on compressional wave velocity in hydrate-bearing sediments

Lijia Li1,2  |  Yongjiang Luo1,2,3  |  Jianming Peng2  |  Zhiwei Liao1,3

1State Key Laboratory of Coal Mine Disaster Dynamics and Control, College of Resources and Environmental Science, Chongqing University, Chongqing, China  
2College of Construction Engineering, Jilin University, Changchun, China  
3Hunan Provincial Key Laboratory of Shale Gas Resource Utilization, Hunan University of Science and Technology, Xiangtan, China

Correspondence
Yongjiang Luo and Jianming Peng, College of Construction Engineering, Jilin University, Changchun, China.  
Emails: luoyj16@cqu.edu.cn and pengjm@jlu.edu.cn

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Abstract
Borehole wall would be disturbed during sampling when drilling into gas hydrate-bearing sediments, thereby changing the reservoir physical characteristics obtained by well logging. It would cause significant errors using such logging data to estimate the reservoir parameters such as hydrate saturation and mechanical properties. In this paper, the theoretical method of combination cavity expansion theory with the time-average equation to predict the compressional velocity ($V_p$) of hydrate-bearing sediment after drilling disturbance were proposed based on the hypothesis that the compaction of hydrate-bearing sediments only causes the porosity change in sediments. The theoretical derivation process of calculation the porosity change caused by drilling compaction based on both Tresca’s yield criteria and Mohr–Coulomb yield criteria were presented in detail. And the influence of drilling compaction on $V_p$ were discussed by theory method developed in this paper and experimental method. Both theory-based results and experimental results show that the $V_p$ difference caused by drilling compaction is considerable. Drilling compaction would cause the increase in $V_p$, and the increment increase with the increase of bit weight, and samples with low hydrate concentrations would be more sensitive to bit weight variations. The proposed method is feasible to simplify the influences of complex processes involved in the disturbance of hydrate-bearing sediments during drilling.

Keywords
compressional wave velocity, drilling disturbance, natural gas hydrate, porous media

I  |  INTRODUCTION

Gas hydrates are ice-like clathrates formed by high pressure–low temperature conditions, and therefore commonly found in marine sediments and permafrost. Natural gas hydrate has attracted worldwide attention due to its potential as a future energy resource and its role in submarine landslides and global warming. The gas hydrate concentration recovered in pressurized core samples has often been used to evaluate natural gas hydrate reserves, but in situ pressurized cores are difficult to obtain due to the narrow range of conditions under which the hydrate is stable. Naturally occurring gas hydrate-bearing sediments are characterized by relatively high acoustic velocities and resistivity relative to unconsolidated water-saturated sediments, therefore they can be used to map the occurrence and concentration of gas hydrates in the process of well logging. Besides, compressional ($V_p$) and shear wave ($V_s$) velocities obtained by wireline logging are often utilized to estimate gas hydrate concentrations. At present, Tinivella and Carcione...
had used well log and seismic data acquired in the Ocean Drilling Program (ODP) to estimate gas hydrate concentrations and $V_p$ and $V_s$ data. Mallik 2L-38 gas hydrate research wells were used to estimate the amount of gas hydrates. Gas hydrate saturations in the Krishna-Godavari Basin were calculated by combining $V_p$ and electrical resistivity data. However, the influence of formation disturbance on geophysical properties was not considered. Meanwhile, most natural gas hydrates occur in relatively young and unconsolidated deposits at water depths of <1500 m. As triaxial shear tests indicated, the mechanical properties of gas hydrate-bearing sediments are similar to those of soft clays and permafrost. Besides, the drilling tools used to obtain pressurized core samples of hydrate-bearing sediments generally have a large outer diameter and small core diameter, such as the piston core system utilized in ODP wells, where the outer diameter of the drill bit is >215.9 mm and the core diameter is <45 mm. Numerous studies have indicated that sediment cores are disturbed during sampling, even when a thin-wall core sampler is used in field sampling for engineering geology. Emery and Dietz concluded that a typical corer used in engineering geology recovers a section that is approximately half as long as the penetration of the instrument into the formation. Therefore, core disturbance is remarkable during gas hydrate sampling because the wall thickness of drilling tools is greater than that of the samplers used in engineering geology. Figure 1 shows an example of a typical disturbed core sample. Hydrate dissociation occurs due to mechanical extension, secondary hydrate formation, and negative pore pressure generation during unloading cause disturbance on core samples. In addition, the rocks near the borehole wall that surround the drilling tools may be compacted and disturbed during sampling. Studies on compaction pile construction have shown that the disturbance due to coring can extend to more than five times of the compaction pile diameter in radial direction, which destroys the structure of sediments and causes a decrease in porosity. Priest et al showed that the ratio of $V_p$ to $V_s$ depends on porosity, confining pressure, and hydrate content, therefore the compaction of gas hydrate-bearing sediments during drilling remarkably alters their geophysical properties. In addition, the use of well log data to calculate the concentration and reserves of in situ natural gas hydrates may produce substantial errors. In present study, we propose a theoretical method that combines cavity expansion theory and time-average equation to estimate the $V_p$ of compacted gas hydrate-bearing sediments. In addition, the influence of compaction on $V_p$ under different gas hydrate concentrations and drill bit weights were discussed.

2 | MODELING DEFORMATION OF HYDRATE-BEARING SEDIMENTS

The forces in front of the drill bit of hydrate-bearing formations during sampling are similar to those during construction of compaction pile. The compaction of hydrate-bearing formation in front of drill bit is a continuous process, and its influence depth in the axial direction of borehole is defined as a unit of length. Therefore, the compaction of hydrate-bearing formation causes deformation only in the radial direction, and this deformation results in a porosity change in the surrounding sediments. Thus, the structural deformation near borehole wall that surrounds the drilling tools can be described using cavity expansion theory. Although the deformation may cause structural failure of hydrate-bearing sediments and influence the compressional wave velocity, which is difficult to consider in the present model due to the complexity of structural failure in this condition. Therefore, only the case where deformation causes a porosity change in hydrate-bearing sediments is considered.

Figure 2 shows a 2D schematic of cavity expansion in an infinite body. For compaction by lateral pressure $p$, the radial direction of the area element experiences compaction, and the tangential direction is under tension. When $p$ is less than critical value ($p_c$), the nearby formation undergoes elastic deformation. When $p$ is greater than $p_c$, plastic deformation of nearby formation occurs and a failure interface $S_c$ forms between plastic deformation area and elastic deformation area. Therefore, the formation surrounding drill bit can be divided into two areas, named as elastic deformation $D_e$ and plastic deformation $D_p$. The balance conditions for an area element can be expressed as:

![FIGURE 1 Photographs of a typical disturbed core from the IODP U1431D borehole](image-url)
For material softening, the deformation in the plastic deformation area $D_d$ can be expressed as

$$f = (\sigma_r - \sigma_\theta) - (\sigma_r + \sigma_\theta) \sin \phi - 2c \cos \phi = 0, \quad (6)$$

where $c$ is the cohesion, $\phi$ denotes the internal friction angle, $c_r$ represents the residual cohesion, and $\phi_r$ indicates the residual internal friction angle of the material. Based on theory and boundary conditions of elastic symmetry problems, the stresses and displacements in the elastic area $D_e$ can be written as

$$\begin{cases}
\sigma_r = p \frac{r_1^2}{r^2}, \\
\sigma_\theta = -p \frac{r_1^2}{a^2}, \\
u = \frac{1+v}{E} \frac{r_1^2}{a^2}.
\end{cases} \quad (7)$$

### 2.1 | Tresca's yield criterion-based deformation

Critical pressure $p_\varepsilon$ of the plastic deformation using Tresca's yield criterion is as follows:

$$p_\varepsilon = K. \quad (8)$$

By combining equations (1) and (4), under the boundary conditions of the drill bit diameter used in this study ($r = a$, $\sigma_r = p$), the stresses in area $D_e$ can be written as

$$\begin{cases}
\sigma_r = p - 2\beta K \ln \frac{r}{a} \\
\sigma_\theta = p - 2\beta K \left(1 + \ln \frac{r}{a}\right).
\end{cases} \quad (9)$$

The boundary of plastic deformation area $r = r_1$, $\sigma_r$ can be calculated as

$$\sigma_{r1} = p - 2\beta K \ln \frac{r_1}{a}. \quad (10)$$

By combining equations (7) and (10), at the boundary plastic deformation area, the stresses and displacements in elastic area $D_e$ can be written as

$$\begin{cases}
\sigma_r = \left(p - 2\beta K \ln \frac{r_1}{a}\right) \frac{r_1^2}{r^2}, \\
\sigma_\theta = -\left(p - 2\beta K \ln \frac{r_1}{a}\right) \frac{r_1^2}{a^2}, \\
u_r = \frac{1+v}{E} \frac{r_1^2}{r^2}.
\end{cases} \quad (11)$$

The displacement at interface $S_e$ can be expressed as $u_1 = \frac{1+v}{E} \frac{r_1^2}{a} r_1$. On the basis of the displacement of symmetric condition ($u = \frac{u_2}{r} a$, where $u_2 = \frac{1+v}{E} \frac{r_1^2}{a} \sigma_r$) and the continuity of
displacement at \( r = r_1 \), the displacement at area \( D_d \) can be expressed as

\[
u_r = \frac{1 + \mu \ r_1^2}{E} \ r \ \sigma_r.
\]

(12)

Based on the condition of interface stress \( S_c \), the relationship between \( p \) and \( r_1 \) can be expressed as

\[
r_1 = a \ e \ \frac{\pi}{2}.
\]

(13)

### 2.2 Mohr-Coulomb yield criterion-based deformation

Critical pressure \( p_c \) of plastic deformation using Tresca’s yield criterion is applied is as follows

\[
p_c = c \cos \phi
\]

(14)

By combining equations (1) and (6), under the boundary conditions of the drill bit diameter used in this study (\( r = a \)), \( \sigma_r = p \), the stresses in area \( D_d \) can be written as

\[
\sigma_r = (p + c \ cctg \phi_c) \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c
\]

\[
\sigma_\theta = \frac{1 - \sin \phi_c}{\sin \phi_c} \ [p + c \ cctg \phi_c] \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c
\]

(15)

And the boundary of plastic deformation area \( r = r_1 \), \( \sigma_r \) can be calculated as

\[
\sigma_{r1} = (p + c \ cctg \phi_c) \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c
\]

(16)

By combining equations (7) and (16), at the boundary plastic deformation area, the stresses and displacement in elastic area \( D_e \) can be written as

\[
\sigma_r = \frac{r_1^2}{r} \left[ p + c \ cctg \phi_c \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c \right]
\]

\[
\sigma_\theta = -\frac{r_1^2}{r} \left[ p + c \ cctg \phi_c \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c \right]
\]

\[
u_r = \frac{1 + \mu \ r_1^2}{E} \ (p + c \ cctg \phi_c) \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c
\]

(17)

The displacement at interface \( S_c \) can be expressed as

\[
u_{r1} = \frac{1 + \mu \ r_1^2}{E} \ r \ \sigma_{r1}
\]

Based on the displacement of symmetric condition \( (u = \frac{\phi_d}{a} u) \), the continuity of displacement at \( r = r_1 \), the displacement at area \( D_d \) can be expressed as

\[
u_r = \frac{1 + \mu \ r_1^2}{E} \ r \ (p + c \ cctg \phi_c) \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c
\]

(18)

Based on the condition of interface stress \( S_c \), the relationship between \( p \) and \( r_1 \) can be expressed as

\[
r_1 = a \ (\frac{p + c \ cctg \phi_c \ (\frac{a}{r_1})^{\frac{2 \ \sin \phi_c}{\sin \phi_c + 2 \ \sin \phi}} - c \ cctg \phi_c)}{cctg \phi_c + c \ cctg \phi_c}
\]

(19)

### 2.3 Calculation of the compaction caused by drilling disturbance

On the basis of Rankine's active earth pressure theory, \( p \) can be calculated as

\[
\begin{align*}
p & = \left( \frac{1}{2} \gamma h^2 + p_0 H \right) K_n - 2cH \sqrt{K_n} \\
K_n & = \frac{1 - \sin \phi}{\sin \phi} \tan^2 \left( 45^\circ - \frac{\phi}{2} \right)
\end{align*}
\]

(20)

where \( K_n \) is coefficient of Rankine’s active earth pressure, \( p_0 \) indicates the bit weight, \( H \) refers to the unit of depth for the compaction of hydrate-bearing formation in front of the drill bit and equal to 1, and \( \gamma \) signifies the unit weight of the formation. In comparison with bit weight \( p_0 \), the pressure caused by the weight of formation surrounding the drill bit \( \left( \frac{1}{2} \gamma H^2 \right) \) is small and consequently ignored. Therefore, equation (20) can be rewritten as

\[
p = p_0 \tan^2 \left( 45^\circ - \frac{\phi}{2} \right).
\]

(21)

Elastic deformation is not considered in present study because it would be recovered after drilling. Then, volume change \( V_{com} \) of plastic deformation area can be calculated as

\[
V_{com} = u_{r} - u_{r1}
\]

(22)

On the basis of the initial hypothesis, only the volume compaction caused by drilling disturbance is considered in this study. Therefore, the volume compaction would only change the porosity of hydrate-bearing sediments. The hydrate-bearing sediments, with original porosity of \( \phi \), original hydrate saturation of \( S_h \), disturbed porosity \( \phi_d \) and disturbed hydrate saturation \( S_d \), can be calculated as

\[
\frac{\phi_d}{\phi} = \frac{(r_1 - a) \phi - V_{com}}{(r_1 - a) \phi - V_{com}}
\]

\[
S_d = \frac{(r_1 - a) \phi - V_{com}}{(r_1 - a) \phi - V_{com}}
\]

(23)

### 3 Calculating the P-wave velocity of the disturbed formation

Several relationships between seismic velocity and gas hydrate saturation have been proposed, including Wyllie’s
time-average equation\textsuperscript{,34} Woods’ relation\textsuperscript{,35} and effective medium modeling based on rock physics\textsuperscript{.36} A three-phase time-average equation based on Wyllie’s time-average equation\textsuperscript{37} is utilized in this study.

The three-phase time-average equation used to estimate the $V_p$ of disturbed hydrate-bearing sediments can be expressed as $^{34}$:

$$\frac{1}{V_p} = \frac{\phi_d(1-S_d)}{V_w} + \frac{\phi_pS_d}{V_h} + \frac{1-\phi_d}{V_m},$$

where $V_p$, $V_w$, $V_h$, and $V_m$ are the P-wave velocities of hydrate-bearing sediments, water, pure hydrate, and the matrix.

### 4 | Estimating the P-wave velocity of disturbed hydrate-bearing sediments

Shear strength which is related to the stability of hydrate-bearing sediments, is a crucial factor to predict submarine slope instability and other geo-hazards. Therefore, considerable efforts have been exerted to determine the mechanical properties of hydrate-bearing sediments in natural and artificial samples. To confirm the influence of drilling disturbance on $V_p$, the mechanical properties of natural and artificial samples synthesized by Masui et al\textsuperscript{,38,39} are utilized in this study, as shown in Table 1. $V_w = 1.5$ km/s, $V_h = 3.3$ km/s, and $V_m = 5.98$ km/s are used.

### 4.1 | Calculated disturbance of hydrate-bearing sediments

Figures 3 and 4 show Tresca’s yield criteria based on disturbed radius and average porosity changes with bit weights, respectively. With a constant hydrate saturation sediment, a major bit weight would remarkably enlarge the plastic deformation area. In addition, the disturbed radius rapidly increases when the bit weight values are high, which is similar with average porosity change. For hydrate-bearing sediments with different hydrate saturations, the disturbed radius is small when the hydrate saturation of sediment is high, and porosity is sensitive to bit weight when the hydrate saturation of sediment is low.

### 4.2 | Estimating the P-wave velocity of disturbed hydrate-bearing sediments

Figure 5 presents the estimated values $V_p$ between disturbed samples with 14t bit weight and undisturbed hydrate-bearing sediment samples with different hydrate saturations. The disturbance causes a remarkable change in $V_p$, especially for sediments with low hydrate saturation, and the difference in $V_p$ ($\Delta V_p$) between the disturbed and undisturbed hydrate samples decreases with the increase in hydrate saturation. Although the relationship between $\Delta V_p$ and natural gas hydrate saturation is unclear for samples 5\# to 7\#, which may be due to the sediment difference between the samples, as shown in Table 1, the initial porosity of these samples are different. For natural gas hydrate-bearing sediments, the occurrence of hydrates in porous media can enhance the shear and compressive strengths because they can act as cementing agent.\textsuperscript{39} Besides, the cementation degree depends on hydrate saturation, in which high hydrate saturation increases the shear and compressive strengths of hydrate-bearing sediments. In addition,
the compaction degree of hydrate-bearing sediments near the drill bit caused by bit weight decreases at high saturations.

Figure 6 displays the influences of bit weight on the $\Delta V_p$ of natural hydrate-bearing sediment. As the pressure exerted on the borehole wall is proportional to the bit weight, increasing the bit weight would increase the compaction of hydrate-bearing sediments. Therefore, the $\Delta V_p$ of hydrate-bearing sediments with constant hydrate saturation increases with the increase of bit weight. To sum up, low-saturation hydrate-bearing samples are sensitive to bit weight due to their low shear, compressive strengths and high porosity.

4.3 Hydrate saturation deviation $\Delta S_h$ caused by drilling compaction

Figure 7 shows the deviation of natural gas hydrate saturation $\Delta S_h$ caused by drilling compaction. Considering natural gas...
hydrate decomposition is ignored in this study, although field drilling could cause hydrate decomposition and it is difficult to consider at present, the compaction in drilling process only increases hydrate saturation. \( \Delta S_h \) can reach to approximately 0.03 when initial \( S_h = 0.266 \). Therefore, high drill bit weight and drilling compaction can cause considerable estimation errors of natural gas hydrate.

5 | EXPERIMENTAL TESTS ON \( V_p \)

CHANGE CAUSED BY COMPACTION

To evaluate the effect of drill bit compaction on the compressional velocity of hydrate-bearing sediments, a series of experimental tests was conducted using an experimental apparatus, as shown in Figure 8. A polytetrafluoroethylene tube with an inner diameter of 70 mm surrounded by a steel tube was utilized to contain the samples. Besides, the sample tube was surrounded by an insulating cozy, which connected to a thermostatic bath with temperature range from \(-20^\circ\text{C}\) to \(50^\circ\text{C} \) (\(\pm 0.1^\circ\text{C}\)), and two pistons with a hollow area for accommodating the ultrasonic probe were placed at each end of the sample tube. Computer-controlled pressure testing machine was used to apply load to the samples via the two pistons. A ZBL-U520 non-metal acoustic detector was utilized to send and receive electrical signals. Two 250 kHz piezoelectric transducers were fixed at the top and bottom of the test apparatus, which can send and receive Ultrasonic waves, and measure \( V_p \). The sampling interval was 0.4 \(\mu\text{s}\), with an excitation voltage of 250 V.

Several studies have indicated that use of pore-water samples or wetted sands to synthesize hydrates would cause heterogeneous hydrate distribution due to the moisture migration during the hydrate formation process.\(^{40-46}\) and the hydrate distribution in porous media is difficult to control. However, the compressional velocity of hydrate-bearing sediments is sensitive to hydrate distribution.\(^{47}\) Previous studies have shown that most physical properties of ice are similar to those of natural gas hydrates, and the properties of permafrost are commonly comparable with those of hydrate-bearing sediments.\(^{48,49}\) Therefore, we used ice as a gas hydrate analogue in our experiments. The samples comprise quartz sand with a grain size of 0.15-0.3 mm and 44.34% porosity, and all sand samples are dried in a drying oven at a temperature of 100°C for 24 hours before use. To ensure homogeneous water distribution in the pores, ice seeds formed by distilled water (0.075-0.15 mm) were uniformly mixed in the samples. Then, the samples were loaded into the sample tube in several 20 mm-thick layers. Controlling the thickness of each layer and tamping times, to ensure various samples can be compared, and all operations were conducted under frozen conditions to limit the melting of ice seeds. The temperature was increased to allow the melting of ice seeds. Subsequently, the thermostatic bath was connected to the sample tube to reduce the temperature and re-freeze the sample. The designated load was applied to the sample and the compressional velocity was measured under constant load.

Nine samples with ice saturations from 0% to 80% at uniform steps of 10% were tested under varying compressional stress conditions (Table 2). Considering the dissipation of loose sands, ultrasonic signals cannot be transmitted through the sample without ice until the compressional stress reaches a critical value. The compressional velocity remarkably increases with the increase in ice saturation and compressional stress, and \( V_p \) significantly increased after the loading process when samples contain ice seeds. As results verify, the compaction of drill bit during drilling considerably changes the compressional velocity of hydrate-bearing sediments.

Figure 9 shows the influences of compressional stress on the \( \Delta V_p \) of ice-bearing samples, and \( V_p \) remarkably increases with compressional stress before reaching a constant level when ice saturation is <20%. By contrast, samples with ice saturations of 30%-60% are slightly affected by compressional stress, and \( V_p \) rapidly increases with the increase in compressional stress. Subsequently, \( V_p \) reaches a constant level. \( V_p \) decreases during the initial loading stage and linearly increases with compressional stress when the ice saturation is >70%. The influence of compressional stress on \( V_p \) can be attributed to three factors, the original internal structure damage of ice-bearing porous sample that results in a decrease in \( V_p \), the compaction of ice-bearing sample, and the increase of contact stiffness of sand particles caused by compressional stress, which can increase \( V_p \). The observed change in \( V_p \) can be explained by the influence of the original internal structure damage of the compaction domain during the early loading stage, and the increased contact stiffness of sand particles governs the change in \( V_p \) during the later stages of the experiment. For samples with ice saturations <20%, the
increase in $V_p$ is attributed to the compaction at the beginning of the experiment, and the increased contact stiffness of sand particles caused by compressional stress increases $V_p$ when compaction reaches a critical value. However, the influence is limited due to the enhanced rigidity of sand particles. For ice saturations $>30\%$, the influence of the original internal structure damage gradually emerges. The influence of the original internal structure damage on $V_p$ is more remarkable than that caused by compaction when ice saturation reaches 70\%, which decreases $V_p$ during the early loading stages.

The experimental results indicate that compaction remarkably influences $V_p$ of hydrate-bearing sediments, and the influence is more substantial than that estimated by the theoretical method developed in the present study.
differences between the theoretical method and experimental results can be attributed to the difference in stress conditions and samples. In addition, the theoretical method does not consider the change in $V_p$ caused by the destruction of the sediment structure.

6 | CONCLUSIONS

A theoretical method that combines cavity expansion theory and time-average equation to estimate the $V_p$ of compacted gas hydrate-bearing sediments was proposed on the basis of the hypothesis that the compaction of hydrate-bearing sediments causes a change in porosity. Besides, factors, such as hydrate decomposition, drilling fluid invasion, and sediment structure deformation, were not considered in the present stage although they cause a change in the $V_p$ of hydrate-bearing sediments. The proposed method simplified the influences of complex processes involved in the disturbance of hydrate-bearing sediments during drilling. Apart from the influence of compaction on $V_p$, the effect of gas hydrate concentration and bit weight was investigated through experimental and theoretical methods. As results showed, the variations in compressional stress remarkably increase the $V_p$ of hydrate-bearing sediments, and the increase in drill bit weight or compressional stress increases $\Delta V_p$ at a given hydrate saturation. Besides, $V_p$ remarkably changes at low drill bit weights in sediments with low hydrate saturations. Although differences are observed between the experimental and theoretical results, the overall trends are the same. Therefore, the differences between the experimental and theoretical $V_p$ values are due to the changes in stress conditions and sample variables, and the theoretical method does not consider the change in $V_p$ caused by sediment structure damage.

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CONFLICT OF INTEREST

There are no conflicts of interest.

NOTATION

- $p$: Lateral pressure, MPa.
- $p_c$: Critical pressure, MPa.
- $p_0$: Bit weight, MPa.
- $S_e$: Plastic and elastic interface.
- $D_e$: Elastic deformation area.
- $D_d$: Plastic deformation area.
- $a$: Outer radius of the drill bit, m.
- $r_1$: Outer radius of the plastic deformation area, m.
- $\sigma_r$: Circumferential stress, MPa.
- $\sigma_r$: Radial stress of material, MPa.
- $\mu$: Poisson's ratio of material.
- $E$: Elastic modulus, MPa.
- $K$: Material coefficient for Tresca's yield criterion, MPa.
- $\beta$: Softening coefficient of material.
- $c$: Cohesion of material, MPa.
- $\phi$: Internal friction angle of material.
- $c_r$: Residual cohesion of material, MPa.
- $\phi_r$: Residual internal friction angle of material.
- $u_r$: Displacement at the radius of r, m.
- $u$: Displacement of the formation, m.
- $u_a$: Displacement at the $r = a$, m.
- $K_p$: Coefficient of Rankine's active earth pressure.
- $V_{com}$: Volume change of plastic deformation area, m$^3$.
- $\gamma$: Unit weight of the formation, kg/m$^3$.
- $H$: Depth for the compaction of hydrate-bearing formation, m.
- $\phi$: Original porosity of the hydrate-bearing sediment.
- $S_h$: Original hydrate saturation.
- $\phi_d$: Porosity after disturbed.
- $S_d$: Hydrate saturation after disturbed.
- $V_p$: P-wave velocities of hydrate-bearing sediments, km/s.
- $V_w$: P-wave velocities of water, km/s.
- $V_h$: P-wave velocities of pure hydrate, km/s.
- $V_m$: P-wave velocities of matrix, km/s.
- $\Delta V_p$: Difference in $V_p$ between the disturbed and undis- turbed hydrate samples, km/s.

ORCID

Yongjiang Luo 🐝 https://orcid.org/0000-0003-1643-7015

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