Engineering Geology 196 (2015) 24–36

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Effect of high hyperbaric pressure on rock cutting process

M. Alvarez Grima [a,*], S.A. Miedema [b], R.G. van de Ketterij [a], N.B. Yenigül [a], C. van Rhee [b]

[a] MTI Holland B.V., Smitweg 6, 2963 AW Kinderdijk, The Netherlands
[b] Delft University of Technology, Section of Dredging Engineering, Mekelweg 2, 2628 CD Delft, The Netherlands

ARTICLE INFO

Article history:
Received 2 July 2014
Received in revised form 5 June 2015
Accepted 20 June 2015
Available online 27 June 2015

Keywords:
Rock cutting
Hyperbaric pressure
Fracture propagation
Time dependence

ABSTRACT

When cutting rock hyperbaric, two cases may occur. The rock may encounter dilation or compaction due to shear. Dilation results in pore under pressures, while compaction results in pore overpressures. Dilation will increase the cutting forces considerably, while compaction may decrease the cutting forces. In both cases the cutting process is supposed to be cataclastic. To dimension cutting tools for deep sea mining, the worst case should be investigated, which is the dilatant case. To understand the cutting mechanism experiments are carried out in a pressure tank, simulating the hyperbaric conditions. Hyperbaric cutting appears to be very different from atmospheric cutting due to the pore water pressures. The experiments have revealed that the cutting mechanism changes from a chip type mechanism under atmospheric conditions to a cataclastic (crushed) type under hyperbaric conditions, resulting in higher cutting forces.
An analytical model is presented to estimate the cutting forces under high hyperbaric conditions. The results obtained with the analytical model agree rather well with the experimental data.

1. Introduction

When cutting rock hyperbaric, two cases may occur. The rock may encounter dilation or compaction due to shear. Dilation results in pore under pressure, while compaction results in pore over pressures. Dilation will increase the cutting forces considerably, while compaction may decrease the cutting forces. In both cases the cutting process is supposed to be cataclastic. To dimension cutting tools for deep sea mining, the worst case should be investigated, which is the dilatant case. To understand the cutting mechanism experiments are carried out in a pressure tank, simulating the hyperbaric conditions.

Hyperbaric cutting appears to be very different from atmospheric cutting due to the pore pressures. The experiments have revealed that the cutting mechanism changes from a chip type mechanism under atmospheric conditions, to a cataclastic (crushed) type under hyperbaric conditions.

In front of the chisel the rock is crushed and shearing of the crushed rock results in dilation, resulting in pore under pressures. These under pressures increase the effective stress and thus also the frictional shear stress. These under pressures depend on the magnitude of the dilation or the magnitude of the dilation and the permeability of the crushed rock and are limited by the water vapor pressure. Because of the very low permeability of the crushed rock, cavitation is expected to be in effect of low to very low cutting velocities. The experiments were carried out at different velocities in order to quantify this effect. From these experiments it was found that cavitation occurred already at low velocities and that the forces can be predicted well with the modified sand cutting equations. Further it appeared that the cutting mechanism has changed in more than one way. Not only the mechanism become cataclastic, but also the 3D chip pattern with a sideways shape has become more a box cut, just following the shape of the chisel. The experiments have proven that in the type of rock chosen, strong hyperbaric effects occur, which in terms of cutting forces, can be described for the cavitating case, with the theory given in the paper.

The increase in cutting forces can be explained by analyzing the combined effect of cutting speed and hyperbaric pressure during the rock cutting process.

According to previous studies reported in the literature, it appears that the understanding of the cutting mechanism at high hyperbaric pressures is rather limited. Most of the studies conducted are mainly concerned with drill bits; cutting a very thin layer of rock (<1 mm). An understanding of the mechanism of rock cutting at large water depth is a requisite for proper design of rock cutting tools cutting a layer of centimeters.

Several rock cutting theories have been published in the literature such as (Evans, 1961, 1962, 1965; Goktan, 1995, 1997; Nishimatsu, 1972). These theories concern rock cutting under dry and/or atmospheric conditions. They cannot be used to estimate the rock cutting forces under hyperbaric conditions because the pore water pressure and the effect of the cutting speed are not taken into account.

Kaitkay and Lei (2005) conducted lab experiments on the influence of hydrostatic pressure on rock cutting with drill bits on Carthage

* Corresponding author.
E-mail address: m.alvarezgrima@mtiholland.com (M. Alvarez Grima).

http://dx.doi.org/10.1016/j.enggeo.2015.06.016
0013-7952/

marble. They found that the increase of confining pressure transformed the cutting process from a brittle to a ductile–brittle failure mode. Longer chips were formed and the cutting forces increased with high hydrostatic pressure.

Van Kesteren (1995) examined the effect of pore water pressure in rock by distinguishing two limiting conditions: drained and undrained. In the drained condition, pore water flow due to pore water pressure gradient is possible without affecting the porous system itself. In the undrained condition pore water is not allowed to flow through the pores and the pore water pressure will affect the stress state in the rock fabric. The drained condition, undrained condition, and the transition zone are determined by the Peclet number. It relates the cutting speed, cutting depth, and the diffusivity coefficient, which in turns depends on the permeability, compressibility of the rock skeleton, compressibility of water, compressibility of rock grains, and porosity. Additionally van Kesteren (1995) explained that the pore pressures are of influence on crack initiation and propagation. He argues that at the strain rates occurring during dredging (order of $10^3\ s^{-1}$), the pore water is able to flow towards the crack tips (drained condition), the transition towards undrained condition occurs at strain rate larger than $10^5\ s^{-1}$. This implies that crack initiation is not impeded by the resistance of the water pressure. At high hyperbaric conditions, however, a different situation might occur regarding the speed of the process, strain rate, and ambient pressure. This in fact, constitutes the main objective of this study. The magnitude of this hyperbaric effect will probably depend on the ratio of the hydrostatic pressure and the unconfined compressive strength of the rock.

Detournay and Atkinson (2000) investigated the influence of pore pressure on the drilling response in low-permeability shear dilatant rocks. Different pore pressure regimes were identified, which were controlled by a dimensionless number. They found that in the high speed regime, the rock in the shear zone is undrained and pressure drops induced by shear-induced dilatancy, which leads to cavitation.

Huang et al. (1999) investigated the effect of cutting depth numerically by using DEM. They found that the ductile failure mode in rock cutting is characterized by a steady flow of a crushed material ahead of the cutter. The brittle failure is characterized by the coalescence of micro cracks and possibly formation of chips. They concluded that the transition between ductile and brittle failure mode in rock cutting depends on the depth of the cut.

Al-Shayea et al. (2000) investigated the effect of confining pressure and temperature on mixed-mode (I–II) fracture toughness of a limestone. Tests were conducted under an effective confining pressure of 28 MPa, and a temperature of up to 116 °C. They found a substantial increase in fracture toughness under confining pressure. The pure mode-I fracture toughness K_{IC} increased by a factor of about 3.7 under a confined pressure of 28 MPa compared to that under atmospheric pressure. The pure mode-II fracture toughness K_{IIC} increased by a factor of 2.4 for a confining pressure of 28 MPa. The effect of temperature was only 25% more for K_{IC} at 116 °C.

Sang et al. (2003) investigated the strain-rate dependency of the dynamic tensile strength of rock. The fracture processes were analyzed at various strain-rates. They found that higher strain rates generated a large number of micro cracks, which interfered with the formation of the fracture plane. The observed increase in dynamic strength at high strain rate was caused by crack arrests due to the generation of a large number of micro cracks.

Funatsu et al. (2004) studied the combined effect of increasing temperature and confining pressure on the fracture toughness of clay bearing rocks. They found that the fracture toughness of sandstone increased by approximately 470% at 9 MPa confinement over its value at atmospheric pressure.

Schmidt and Huddle (1997) investigated the effect of confining pressure on fracture toughness of Indiana limestone. They found that K_{IC} increased from 0.93 MN $m^{-3/2}$ at atmospheric pressure to 4.2 MN $m^{-3/2}$ at a confining pressure of 62 MPa.

Zijsling (1987) found that due to low permeability, cavitation will occur in the crushed zone, even with very small layer thicknesses. The result, combined with narrowing to a box cut, implies that the full width of the cut has to be covered with chisels/pick points. So different rows of chisels have to be staggered in contrary with atmospheric cutting where there is overlap due to the 3D effect.

From the studies presented in the literature, it can be concluded that high hyperbaric pressure affects the rock behavior and particularly the fracture toughness, crack initiation and propagation. This of course will depend on the rock material properties such as porosity, permeability, and elasticity (plasticity). It is expected that cutting rock at large water depth will have a strong effect on the magnitude of the cutting forces and energy required.

2. Time dependency of fracture initiation and propagation

This section discusses the impact of time and speed on the cutting process. The cutting process is divided into three different subprocesses — (*i*) forming of a crushed zone, (*ii*) fracturing by shear failure, and (*iii*) fracturing by tensile failure. Each of these sub-processes is influenced by the speed of the cutting process. A dimensional analysis has been carried out to estimate the impact of the different factors on the cutting process and establishing in this way the basis for the selection of the parameters that will be investigated in the laboratory (see Table 1). The dimensional analysis was carried out by using the Buckingham theorem.

Fig. 1 schematizes the phenomena involved in the chip forming process during rock cutting for shallow (Verhoef, 1997), and for deep water conditions. It is assumed that under high hyperbaric pressure (about 20 MPa) the failure mechanism will be predominantly shear, in contrast to a typical shallow cutting process where the failure mechanism will be predominantly tensile. The extension of the crushed zone in front and below the cutting tooth is expected to be larger for high hyperbaric pressure.

(i) *Forming of a crushed zone*: In this part of the process the cutting tool penetrates the rock and crushes it. The rock compressive strength will be exceeded. Grains will be pulled out of the joints, pulverized, and pushed into the pores of the material further away from the cutting tool. The water in the pores will be pushed further away into the material, resulting in high pore pressure. Water flow in the pores is governed by Darcy's law. If the cutting speed is increased, the fluid velocity in the pores will have to increase too. This can only occur if pressure difference increases. The pore pressure near the tool tip has to decrease considering a pore pressure away from the tool tip approximately equal to the hydrostatic pressure. This has an inevitable influence on the required cutting force, which will increase linearly with pore pressure difference near the tip.

Table 1 lists the parameters influencing the cutting process. When the hydrostatic pressure (P_{hyd}), the volume of crushed zone (V_{cr}), and viscosity (μ) are chosen as running variables the following relation emerges by using the derived dimensionless numbers:

$$\frac{Encr}{P_{hyd}\cdot V_{cr}} = y\cdot\left[\frac{\Delta p}{P_{hyd}},\frac{k^3}{V_{cr}^2},\frac{L^3}{V_{cr}},\frac{V\cdot\mu}{P_{hyd}\cdot V_{cr}^{1/3}},\frac{P_{hyd}\cdot t}{\mu},\frac{D_{grain}^3}{V_{cr}},\frac{E_{grain}}{P_{hyd}},\frac{E_{matrix}}{P_{hyd}},\frac{P_{hyd}\cdot V_{cr}^{2/3}\cdot\rho}{\mu^2},\frac{\sigma_{11}}{P_{hyd}},\frac{\sigma_{12}}{P_{hyd}},\frac{\sigma_{13}}{P_{hyd}},\frac{L_{tool}^3}{V_{cr}}\right]. \quad (1)$$