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Biconvex versus bilinear force-penetration relationship in percussive drilling of rock

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ABSTRACT

Because of variability of the force vs. penetration relationship (FPR) from one blow to another in percussive drilling, and difficulty to predict FPRs under such conditions, use is commonly made of simple FPR models, such as the bilinear one defined by its loading/unloading slopes. Here a biconvex model with an added parameter representing convexity is considered. One aim is to study the effect of convexity on maximal penetration, maximal force and efficiency. Another is to assess, with the biconvex FPR as an example, how well a bilinear FPR can be used to approximate one that is nonlinear. A simple percussive top-hammer drill model is considered, comprising a hammer, a drill rod and a bit with the same characteristic impedance. The maximal penetration is found to decrease and the maximal force to increase with increasing convexity. The efficiency has a maximum for a finite hammer length (incident wave duration), and the highest maximal efficiency is obtained for a linear FPR. With increasing convexity, the maximal efficiency decreases and occurs for shorter hammers (incident waves). The bilinear approximation of a biconvex FPR accurately predicts the position of the maximum in efficiency, even for large convexity, but somewhat overestimates its height and width.

1. Introduction

Percussive drilling is an efficient method for drilling of hard rock in mining and construction applications. It makes use of a drill bit with hard-metal indenters which are pushed into the rock due to the action of elastic waves. These waves are generated through impacts by a reciprocating hammer, commonly driven by hydraulics or compressed air. When the bit penetrates into the rock, it performs work. Most of this work goes into crushing, while a smaller part builds up elastic strain energy in the rock which is returned when the rock is unloaded. Normally, only a negligible part of the supplied energy is radiated into the rock [1]. The maximal force generated is typically a few hundred kN and the maximal penetration is of the order of a mm. Between impacts the bit is rotated a certain angle and debris is flushed away from the bottom of the drill hole.

The bit-rock interaction is commonly described in terms of a relation between the force acting on the rock and the penetration of the bit into the rock during a loading-unloading cycle. Such a force vs. penetration relationship (FPR) is an important determinant for the performance of a percussive drill, and therefore FPRs have been subjected to theoretical and experimental studies since long, e.g. [2–8]. The FPR and its character depends on the geometry, number and configuration of the indenters, on the geometry and flushing of the hole bottom, and on the properties of the rock material (strength, brittleness, elastic properties, inhomogeneity, etc.).

When a single relatively blunt indenter is pushed into a flat rock surface, the force normally increases smoothly with the penetration, and the rock under the indenter is crushed into a powder. Under such conditions, dimensional analysis leads to an FPR that is linear if the indenter is a long wedge and quadratic if the indenter is a cone (both with large apex angle). A common feature of these cases is that the indenter has no characteristic length. In contrast, a button-shaped indenter with spherical end has a radius as characteristic length. In this case and in similar cases with one or several characteristic lengths, dimensional analyses lead to FPRs that are generally nonlinear without further specification. If the indenter is relatively sharp, crushing alternates with chipping which signifies sudden breakage of larger pieces of rock material. When chipping occurs, the force suddenly drops which makes the FPR complex and irregular.

When a multi-indenter bit is pushed into a flat rock surface, and the distances between the indenters are such that the indenters do not interact with each other, the FPR of the bit becomes the sum of the FPRs for the individual indenters acting alone. This FPR may be less irregular as those of the individual indenters as chipping normally does not occur simultaneously at all indenters. If the indenters interact with each other, the character of the FPR is modified. If the rock surface is irregular, which is normal in rock drilling, all indenters will not get in contact with the rock simultaneously. If contact is established successively by an increasing number of indenters, the

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Nomenclature

Latin

A	cross-sectional area
a	constant $(=(1+8\phi)^{1/2})$
c	wave speed $(=(E/\rho)^{1/2})$
E	Young's modulus
F, f	bit force acting on rock (positive in compression)
k	initial penetration resistance
L	length
N, n	normal force at rod/bit interface associated with waves (positive in tension)
p	bit penetration parameter representing convexity
q	constant $(=\frac{1}{2}(a+1))$
r	constant $(=\frac{1}{2}(a-1))$
T, t	time
U, u	penetration
V	impact velocity
W, w	energy, work
Z	characteristic impedance $(=AE/c)$

Greek

β	dimensionless hammer length or duration of incident wave
γ	unloading/reloading parameter
η	efficiency of conversion of wave energy to work
κ	dimensionless penetration resistance in linear approximation
ρ	density
ϕ	dimensionless measure of convexity

Subscripts

a	amplitude
d	duration
H	hammer
I	incident
M	maximal
R	reflected
r	residual
0	reference

Acronyms

FPR	force-penetration relationship
TPSM	two-point strain measurement

FPR of the bit can be expected to become more convex than that of an individual indenter. For example, the FPR of the bit may become convex if that of an individual indenter is linear. On the other hand, concave parts of an FPR may result if contact is lost by one or several indenters due to breakage of ridges and hills on the rock surface. Clearly, a significant variability of the FPR from one blow to the next can be expected in real drilling.

The two-point strain measurement (TPSM) method [9,10] allows bit force and penetration to be determined as functions of time from measured axial strains at two different axial positions of a drill rod. Therefore it has been used in several experimental studies of FPRs under conditions similar to those in percussive drilling.

TPSM tests with a single wedge-shaped bit (diameter 32 mm, apex angle 120°) acting on a plane concrete surface were carried out by Karlsson et al. [5]. They obtained an FPR that was close to linear during loading and unloading (bilinear) in accord with dimensional analysis.

TPSM tests with a Sandvik Rock Tools button bit (diameter 52 mm, thread R32) and Swedish Bohus Granite were carried out by Carlsson et al. [6]. In these tests the bit at the bottom of a 100 mm deep predrilled borehole was turned 22.5° between the blows. The character of the FPRs obtained differed markedly from one blow to another; sometimes the loading function was mainly convex, sometimes it was mainly concave, and sometimes it had a mixed appearance in accord with the description above.

Similar TPSM tests with a Furukawa button bit (diameter 64 mm, thread T38) and Inada Granite were carried out by Hashiba et al. [8]. They introduced a correction for the force and used a bit model with all axial bit-rod interaction at the bottom of the rod (i.e., no interaction along the threads). In these tests the bit at the bottom of a predrilled borehole was turned 25.7° between the impacts. Although substantial variation in the FPRs was observed, these relationships were deemed convex in loading and unloading (biconvex). This is consistent with results of numerical simulation for penetration of a triple-button bit into Kuru Granite obtained by Saksala et al. [7].

Because of the variability of the FPR during actual drilling and the difficulty of predicting individual FPRs under such conditions, the bit-rock interaction is mostly not described in terms of complex FPR models. Instead, use is made of simple models which are considered to describe a representative behavior. The most commonly used bit-rock interaction model in theoretical studies such as [11–18] is a bilinear FPR, defined by two parameters representing the constant slopes during loading and unloading. Here a corresponding biconvex FPR, with an added parameter representing convexity, is considered. For the value zero of this parameter the FPR is linear and for large values it is close to quadratic. Such parameter values may represent indenters shaped as a wedge and a cone, respectively, with relatively large apex angles. For intermediate values, the FPRs may represent button bits under conditions similar to those in [7,8].

The aim of this paper is twofold. First it is to determine the maximal penetration, the maximal force and the efficiency of a percussive hammer drilling process with biconvex FPR, and to study the effect of convexity. Secondly it is to assess, with a biconvex FPR as an example of a nonlinear FPR, how well a bilinear FPR can be used to approximate one that is nonlinear. A simple top-hammer percussive drill model is considered, comprising a hammer, a drill rod and a bit, all uniform and with the same characteristic impedance. This model represents the main features of some simple but interesting cases of top hammer drilling, and because of its simplicity it facilitates interpretation and does not divert the focus of the study.

At first, the performance of a percussive top-hammer drill with a biconvex FPR will be studied. Then, in Section 3, a bilinear approximation will be established. In Section 4, the maximal penetrations, the maximal forces and the efficiencies obtained with the biconvex FPR and with its bilinear approximation will be compared and discussed, and in Section 5, the main conclusions will be summarized.

2. Biconvex FPR

2.1. Model

A drill rod with a drill bit at its end in contact with the rock is illustrated in Fig. 1(a). An elastic incident wave (I) generated through impact by a hammer propagates through the rod towards the bit where a reflected wave (R) is generated. These waves are commonly much longer than the diameter of the rod and the dimensions of the bit. Therefore, the wave propagation in the rod can be modelled as 1D and the bit can be taken as rigid and massless. The drill rod is assumed to be straight, uniform and elastic with characteristic impedance $Z=AE/c$ and wave speed $c=(E/\rho)^{1/2}$, where A is the cross-sectional area, E is the Young's modulus, and ρ is the density.

At the rod-bit interface, the incident and reflected waves are associated with normal forces $N_I(T)$ and $N_R(T)$, positive in tension, where T is time. The front of the incident wave arrives at the bit at