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Optimal wave shape with respect to efficiency in percussive drilling with detachable drill bit

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ABSTRACT

The problem of finding the optimal incident wave of given duration that maximizes the efficiency of conversion of wave energy into work in percussive drilling with detachable drill bit is considered. The drill rod is modelled as 1D linearly elastic and the drill bit as a rigid mass. The bit/rock interaction is described by a history-dependent force versus penetration relation with different constant slopes for primary loading and unloading/reloading. A functional expressing the dependence of the efficiency on the shape of an arbitrary incident wave of given duration is derived and maximized. For short incident waves, there is a weak influence of the bit mass on the optimal wave shape which is nearly rectangular. For longer incident waves, there is a strong influence of the bit mass on the optimal wave shape which significantly differs from rectangular. The efficiencies for optimal waves approach those for rectangular waves for short waves. For long waves they approach or assume values which are independent of wave duration but decrease with increasing bit mass. Relative to commonly-used rectangular waves significant increase in efficiency can be achieved through optimization of the wave shape if the wave is not too short. Optimal incident waves can be realized accurately, e.g., by piezoelectric means.

1. Introduction

Percussive drilling is mainly used to produce blast holes in mining and construction operations. In a common form of such drilling, called top hammer drilling, the rock drill stays outside the hole, and elastic waves generated through impact propagate through a drill rod or an assembly of such rods towards a drill bit at the bottom of the hole. Normally, the kinetic impact energy is almost fully converted into energy of these waves. The bit may consist of a wedge-shaped cemented carbide insert at a shaped bottom end of a drill rod, or it may be of detachable type. In the former case, the rod and the bit constitute a single piece, called an integral drill steel. In the latter case the bit may be screwed to the rod or attached to it by a conical joint. In this case, use is often made of an assembly of joined rods and of a bit equipped with cemented carbide cutters. Rock debris produced are flushed out of the hole by air or water injected through the drill rod(s) and the bit, and from one impact to the next the bit is rotated a certain angle. A feed system counteracts the backward impulse received by the aggregate of rock drill, drill rod(s) and drill bit from its interaction with the rock.

When an incident wave arrives at the bit, a reflected wave is generated and the two waves produce a force which makes the cutters penetrate into the rock. The penetration has an irreversible part due to crushing and a smaller reversible part due to elastic deformation. Under efficient operating conditions, the work performed on the rock can attain a substantial fraction of the energy supplied by the primary incident wave [1–6]. The remaining energy is associated with the reflected wave. At the rod–hammer interface this reflected wave may be partially reflected back towards the bit, while some of its energy goes into the hammer. Under efficient operating conditions, this secondary incident wave contains little energy and does not contribute significantly to the work performed on the rock [4]. Therefore the effects of this wave and of its successors will be disregarded here.

The work performed on the rock goes into surface energy, elastic strain energy, kinetic energy, heat, and other forms of energy. Most of these energies are deposited within or near the crushing zone, but some energy is also associated with waves radiated into the rock. Estimations have shown [7,8] that the elastic strain energy is significant, while the energies associated with new surfaces and radiated waves are negligible. The appearance of these energies is necessitated by the nature of the percussive drilling process. The specific energy defined as the work required for removal of a unit

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Nomenclature

Latin

A	cross-sectional area
a	constant (=$1/2m$)
b	constant (=$(1-4m)^{1/2}/2m$)
C	constant
c	wave speed $(=(E/\rho)^{1/2})$
E	Young's modulus
F, f	force acting on rock (positive in compression)
g	impulse response
k	penetration resistance during primary loading $(=\mathrm{d}F/\mathrm{d}U)$
M, m	bit mass
N, n	normal force at rod/bit interface (positive in tension)
p	constant $(=a-b)$
q	constant $(=a+b)$
T, t	time
U, u	penetration
V, v	penetration rate
W, w	energy, work
Z	characteristic impedance (=AE/c)

Greek

α	constant (=$4m$)
β	dimensionless duration of incident wave
γ	ratio of loading to unloading/reloading penetration resistances
η	efficiency of conversion of wave energy to work
θ	dimensionless time at which force acting on rock is maximal
ρ	density
ϕ	constant $(=\pi/\omega)$
ω	constant $(=(4m-1)^{1/2}/2m)$

Subscripts

d	duration
I	incident
P	point at which force acting on rock is maximal
R	reflected
0	characteristic quantity

volume of rock is typically of the order of magnitude of the compressive strength of the rock material. The efficiency of wave energy conversion to work at the bit will be defined here as the ratio of the work performed on the rock due to the primary incident wave to the energy supplied by this wave. As for given wave energy supplied the volume of rock removed in an impact cycle is proportional to the efficiency of wave energy conversion and to the inverse of the specific energy, high efficiency and low specific energy are desirable.

In this paper we consider the problem of finding the optimal incident wave that maximizes the efficiency of wave energy conversion to work in top hammer drilling. This problem was first addressed by Long [9] on the basis of theoretical work by Fairhurst [1]. For the case of drilling with integral drill steel, in which the bit can be considered to have zero mass, Long imposed the absence of a reflected wave. By doing this, and neglecting the reversible elastic deformation of the rock, he arrived at 100 per cent efficiency for a semi-infinite optimal wave with exponentially increasing amplitude. If the effect of the reversible elastic deformation of the rock is taken into account, reflection during unloading somewhat reduces the attainable efficiency [4]. Recently, the authors considered the same optimization problem with the practically motivated constraint that the optimal wave should have a given finite duration [10]. Although much more involved, this reformulated problem had a simple solution closely related to Long's optimal wave. Here, another practically motivated feature of the optimization problem is added, viz. the influence of the mass of a detachable drill bit. For this important case we will determine the optimal wave of given finite duration that maximizes the efficiency of wave energy conversion to work. It will be seen that the mass of the bit has a significant influence on the shape of the optimal wave as well as on the achievable efficiency. Comparisons will be made with efficiencies obtained for rectangular waves [4] which are commonly used.

In Section 2 we present a model for percussive drilling with detachable drill bit. The governing equations are established in dimensionless form, and the efficiency of wave energy conversion at the bit is expressed as a functional in terms of the time history at the rod/bit interface of an arbitrary incident wave. This general result is specialized in Section 3 to the case of rectangular incident waves. Then, in Section 4, optimal waves and corresponding maximal efficiencies are derived. Results for rectangular and optimal waves are presented and discussed in Section 5, and main conclusions are summarized in Section 6.

2. Percussive drilling with detachable drill bit

2.1. Model

The lower part of a drill rod with an attached drill bit is illustrated in Fig. 1 (a). An elastic incident wave propagates through the rod towards the bit where it is partially reflected. As the length of the incident wave is commonly much larger than the diameter of the rod and the dimensions of the bit, a 1D model [11,12] is used for the rod and a rigid mass model is used for the bit.

Next to the drill bit, 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. The mass of the drill bit is M. 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 incident wave is assumed to arrive at the bit at time $T = 0$. It is defined by its finite duration T_d, its characteristic force amplitude N_0 (taken to be positive) and its shape illustrated in Fig. 1 (b). The force (positive in tension) acting between the rod and the bit is $N = N_I + N_R$, and the penetration rate is $V = \mathrm{d}U/\mathrm{d}t = (1/Z)(-N_I + N_R)$, where U is the penetration. Thus, the equation of motion of the bit is $M\mathrm{d}V/\mathrm{d}T = -N - F$, where F is the force (positive in compression) acting between the bit and the rock.

The bit/rock interaction is modelled by the history-dependent relation between the force F and the penetration U shown in Fig. 1 (c). The validity of this description has been confirmed by use of identification techniques [5,13,14] based on analyses of waves in drill rods. Recently it has also been confirmed by 3D finite element simulation of the bit penetration process [15]. When primary loading OP takes place, with penetration rate $V > 0$ and loading rate $\mathrm{d}F/\mathrm{d}T = kV$, the penetration resistance is $\mathrm{d}F/\mathrm{d}U = k$, and the positive increments of penetration are due to the combined effect of irreversible crushing and reversible elastic deformation of the rock. At point P and time T_P, the force acting on the rock is maximal. When unloading PQ takes place, with $V < 0$, the slope of the unloading