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Approach to Estimate Rational Parameters of Rock Destruction from a Function of a Cutting Force

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Abstract. One of the main topics in modern mining science is the prediction of the excavation performance. The most used indicators describing excavation efficiency are specific energy and cutting force. At this the last one is of primary concerns of practicing engineers and researchers. Cutting force depends on physical properties of a destructed rock, tool's geometry and technical parameters of the process such as penetration, spacing, etc. Rock properties are almost always considered as unchangeable parameters of the process. So in order to use rationally limited power resources of a machine mechanical excavator's manufacturers and miners only optimize tool's geometry and technical parameters of the process. Most of them are hardly changeable during exploitation. Thus, it is a responsible challenge to estimate optimal values of the parameters that is not still properly executed. The proposed approach is a mathematical, which defines cutting force as a function of a variable. It depends on estimation of such a value of the variable that relates to a specific relation λ between changes of the argument δx and the function δy. The approach could be used not only on the designing stage of a project but also for in-situ decision-making on the changing of a specified parameter depending on permanently build function of cutting force.

1. Introduction

Prediction of the excavation performance of any mechanical excavator for any geological formation is one of the main concerns in determining the economics of a mechanized mining operation. Studies on cutting of rock with mechanical tools started developing in years 1960s. Though they are still progressing and significant efforts have been made to understand the mechanism of rock cutting, to enhance cutting efficiency and tool life, sometimes theoretical and empirical models are not found satisfactory and experimental methods are preferred, but they are almost always time-consuming, expensive, and also usually limited to one rock type and/or one machine type. These methods may be generally classified as the full-scale linear cutting test, the small-scale cutting test (core cutting), empirical approach, semi-theoretical approach and field trial of a real machine [1-5]. The data obtained from these tests are used as input for selection and design of an excavator, selection of cutter, definition of optimum cutting geometry and prediction of mechanical excavators' performance and cost [6].

The most used indicators describing destruction of rock by means of mechanical tools are specific energy and cutting force. At this specific energy depends on cutting force, so the last one is of primary concerns of practicing engineers and researchers. It is highly useful because it allows estimating of a cutterhead torque, and machine power that are required for a particular application which is often limited by rotary and thrust force capacity of a mechanical excavator.

Cutting force depends on physical properties of a destructed rock, tool's geometry and technical parameters of the process such as penetration, spacing, etc. Rock properties are almost always considered as unchangeable (given) parameters of the process. So in order to use rationally limited power resources of a machine mechanical excavator's manufacturers and miners only optimize tool's geometry and process technical parameters. However once chosen only a few of them could be changed without stoppages and/or serious reworks during exploitation. Thus, it is a responsible challenge to estimate optimal values of the parameters that is not still properly executed. So the search for new methods and approaches on the challenge is relevant.

2. Base for the Approach

As it could be concluded from the written above, existing methods and approaches are mostly based on physics modeling in order to try to describe the mechanism of the process. The proposed approach is a mathematical one (but not a statistical). It's critical for the approach to define cutting force as a function of a variable. We need to estimate such a value of the variable that relates to a specific relation λ between changes of the argument δx and the function δy

$$\frac{\delta x}{\delta y} = \lambda \tag{1}$$

The equation (1) could be also stated: the rate of increase of y with respect to x is λ. Let's also point out that dimension of λ is dimension of x related to dimension of y.

The most well known case of determining optimum value of an argument is when λ is equal to zero, which means a turning point of a function that is either a maximum or a minimum of the function. However, we use λ instead of zero or another constant value. There are few reasons for this. Let's name two major of them. The first one is some functions just do not have a turning point, at least within a considered diapason of values. And the second is in fact that sometimes we don't need to know extreme values of a function. Often an extremum of a function is at the coordinate's origin. Usually it's not useful to know that while parameter's value is zero function's value is zero too. It is so because actually no process occurs at the moment. The question of what is the exact value of λ depends on a task as well as features of a parameter and a function. In general case its value could be taken as 1 for monotone function, because it is for an extreme case when the parameter's change leads to an identical change of the function's value, and 0 for functions with extremum (if it's not in coordinate's origin).

3. Examples of Use of the Approach

Nowadays hard rock tunnel boring has become the standard method of tunneling for tunnels of various sizes. Since the first successful use in early 1950s tunnel boring machine (TBM) technology is improved in recent years and at present usage of TBMs is widely getting popularity in mining and civil engineering works. A considerable and valuable amount of design and performance studies for TBMs have been carried out by many researchers in the last years [7-9]. It allowed their continuous transformations by improving installed cutterhead power, size of machines, cutter loading capacity, and designs in order to make machines more efficient and powerful. At this TBM's application are various mining conditions from extremely hard and massive rock to broken and blocky grounds [8]. Even in the most extreme conditions TBMs provide high advance rates and working safety. Unlike the drill-and-blast method it also reduces vibrations as well as extent of the damaged area beyond the planned excavation limit.

It is necessary for planning purposes a reasonably accurate estimation of needed penetration, rate of advance per established time unit (day, month), and summarized cutters cost [10]. In order to justify the use of TBM in any project it is important to design cutter-head satisfying conditions above. At this the key parameters are head diameter, number of cutters, thrust force, rolling force, RPM, penetration depth [7]. But the major challenge is to choose appropriate cutter spacing in order to govern cutting efficiency, because a small deviation from the optimum spacing leads to a significant reduction in cutting efficiency [11, 12]. The effect of the spacing between cuts and penetration on cutting efficiency is explained by a lot of studies of many researchers [7, 11-14]. If cutters are too close to each other, the cutting is not efficient because of over-crushing of the rock. Also in this region, tool wear is extremely extensive due to the high friction between tool and rock, which significantly increases tool consumption [15]. If cutters are spaced too wide, the cutting is not efficient, because cracks from adjacent cuts caused by tensile fractures cannot reach each other to form a chip.

To apply the approach to the task it is needed to have a basic method for prediction of cutting force *F*, which depends on tool's type and on the level of understanding of the cutting process, which has remained one of the phenomena that are not well understood. In TBM applications, the most efficient and most popular cutting tool is a disc cutter with cutting edge of a constant cross section (CCS-type or simply CCS). The most used method for CCS is the one developed by Rostami and Ozdemir [12]

$$F = CRT\gamma \cdot \left(\frac{s\sigma_C^2 \sigma_T}{\gamma \sqrt{RT}} \right)^{1/3} \quad (2)$$

where C is a dimensionless coefficient (≈2.12), R is the radius of disc cutter, mm, T is the cutter tip width, mm, s is the cutter spacing, mm, σ_C is the uniaxial compressive strength of rock, MPa, σ_T is the Brazilian tensile strength of rock, MPa, γ is the angle of the contact between the rock and disc cutter

$$\gamma = \arccos\left(\frac{R-p}{R} \right) \quad (3)$$

where p is the penetration, mm.

Taking the derivative of the function (2), equating it to the λ, and then solving it for the cutter spacing, we got the following equation

$$s = \gamma^2 \sigma_C \cdot \left(\frac{c^3 \sigma_T}{27\lambda^3} \right)^{1/2} \cdot (RT)^{4/5} \quad (4)$$

The equation (4) could be used in order to estimate rational cutter spacing for a process of destruction with a given CCS-type disc cutter (described by parameters R and T), a given geological conditions (uniaxial compressive and Brazilian tensile strengths), and for a given penetration rate (which 'hidden' within γ and is determined by an advance rate needed).

Another types of excavators widely used in underground mining nowadays are longwall shearers [16] and roadheaders [17]. They are almost always equipped with point-attack picks, which are of a conical shape with a round tip, inserted axisymmetrically into a cylindrical shank so that they are free to rotate during cutting in order to be more evenly worn [18].

Only a few models have been proposed in the literature for obtaining cutting force while cutting rock with point-attack pick. It is so due to the fact that the cutting by a point-attack pick is fundamentally three-dimensional, and is difficult to be simplified [18] in order to reveal the mechanism of rock destruction.

The most well known of them is the Evans' model [19], which claimed that the total penetration force was equivalent to the normal force between the material and the pick, leading to the following maximum penetration force of the pick to break the material

$$F = \frac{16\pi\sigma_T^2 d^2}{\sigma_C \cos^2\theta} \quad (5)$$

where d is the depth of cut, mm, θ is the half conical angle of the point-attack pick, degrees.

The next presented models on the topic [20-22] are actually extensions of the Evans' model by including the effect of pick attack angle and friction between the pick and the material to cut.

Taking the derivative of the function (5), equating it to the λ, and then solving it for the depth of cut, we got the following equation

$$d = \frac{\lambda \sigma_C \cos^2 \theta}{32 \pi \sigma_T^2} \tag{6}$$

Let us also point out the tiny difference between depth of cut in equation (5) and penetration in equation (3) in terms of rock cutting is in the following. Under penetration cross-section of the destructed material is almost equal (or about it) to the cross-section of tool's part (in both cases cross-section is normal to the vector of tool's speed). In its turn depth of cut is a penetration that produces a radial compressive stress in the material to cut. When the hoop stress in the material reaches its tensile strength, breakage happens and a symmetric, V-shaped chip segment is produced.

4. Conclusions

Above there are represented the approach's implies to the most well-known theoretical methods of performance prediction for the most used mechanical tools in the modern mining. Spacing and depth of cut are the main technical parameters in mining regarding excavation by mechanical method. Therefore, equations (4) and (6) are useful by themselves. At this, another purpose of them here is to demonstrate the principle of the approach. It is not limited to the cases given. Promising application for it is in-situ decision-making of the changing of a specified parameter depending on permanently build function of cutting force on it.

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