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Full Length Research Paper

An analytical pre-feasibility study to generate rotary-percussive concept in hard rock TBMs

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In this paper, an analytical modeling has been carried out to realize the effect of appending a supplementary percussive load to the rotary energy of tunnel boring machine's disc cutters, as a novel technology. In this path, two models have been built by using the theory of plasticity for prediction of the amount of penetration of a disc cutter assumed in form of a V-shaped indenter in rock medium. Since the types of applied loads at two phases (rotary versus percussive) differ, it was obligatory to consider different analytical models for each phase. At first stage of the modeling process, a part of previously constructed model for determination of tool penetration into rock has been used. Then, at the next stage, the depth of penetration resulted from the impacts of a striker on the disc cutter has been modeled by using the kinematic method. The aggregative penetration of the disc by application of rotary-percussive load has been considered as non-algebraic summation of penetrations in two stages. Finally, an illustrative example has been presented to show the application of the models in a real situation. In both models, the friction between penetrating tool and the rock has been taken into account.

Key words: Novel rotary-percussive technology, hard rock TBM, analytical modeling, disc penetration.

INTRODUCTION

Nowadays, tunnel boring machines (TBMs) are widely used in excavation of rocks in tunneling, road and construction engineering. TBMs which are utilized in these engineering projects usually require high input powers. Though, as drilling, mining and tunneling environments are becoming increasingly severe; advancements through drilling optimization are needed to hold down costs. The rate of penetration, bit life and cost of maintenance are the major factors of this technology. Among these factors, the rate of penetration is the most important one which has been studied by many researchers. Most of researches have been directed in ways so that affect this factor in an increasing manner. Disc cutters are the most commonly used tools on the face of TBMs in hard rock conditions. During the excavation, TBM cutters roll across the tunnel face and continuously expand the crushed zone immediately beneath them, with the help of thrust energy. In general, rock cutting with a TBM involves the indentation of a rock surface by cutting tools, which are mounted in an array on the front of a cutterhead. Many researchers have supposed the penetration mechanism of the discs as indentation. The main research work on rock indentation and cutting started in the 1970's. Among them are those carried out by Pariseau and Fairhurst (1967), Nishimatsu (1972), Roxborough and Phillips (1975a, 1975b), Lindqvist (1982), Cook et al. (1984), Lindqvisat et al. (1994), Kou (1995), Swoboda and Abu-Krisha (1999); Liu (2003), Kou et al. (2004), Swoboda et al. (2004), Gong et al. (2005), Gong et al. (2006), Innaurato et al. (2006) and Gertsch et al. (2007). These studies have totally been done in conventional conditions of loading process. However, some studies have been performed to utilize dynamic loads as a supplementary energy to achieve higher rates of penetration and also lower power supplies by the machine as novel technologies. Knickmeyer and Baumann (1981) utilized a high-frequency oscillator on axis of the cutter. The results showed that dynamic loads in form of oscillation have great influence on the rate of penetration of the cutter. Their designed system is named "Activated Roller Cutter (ARC)". Hood and Alehossein (2000) designed a new oscillating disc cutting (ODC) system which was capable of breaking very hard rock at acceptable-

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Figure 1. A close view of disc cutter (manufactured by Robbins Co.).

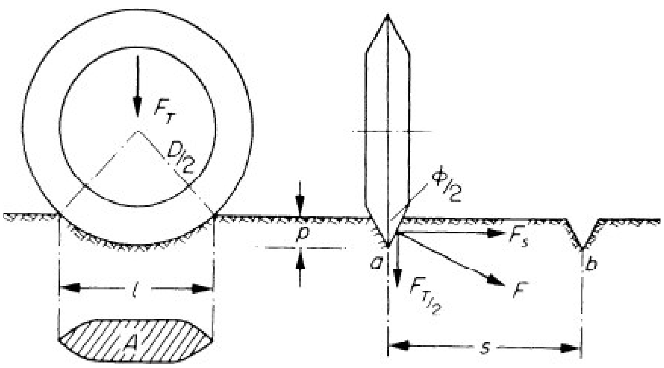

Figure 2. Geometry of disc penetration (Roxborough and Phillips, 1975a).

to-good excavation rates with very low cutter forces mainly through the dynamic energy in form of oscillation.

Despite the application of this kind of dynamic energy in the past, percussive loads seemed to be more efficient because of the greater amplitude in unit of time of wave propagation. This research is done as the earliest part of a current comprehensive project for presentation of the new rotary-percussive technology applicable in TBMs, at the Rock Mechanics Laboratory of Shahrood University of Technology, Iran. In this paper, the effect of appending a supplementary percussive load to the rotary energy of TBM disc cutters has been analytically investigated. In second section, firstly a general description about cutting tools of TBMs and penetration process is presented. Then, analytical modeling including two different phases of the penetration of disc cutter into rock medium is done. Subsequently, in Section 3 an illustrative example for application of the derived formulae is presented. Eventually, in Section 4, a discussion about the subject and the performed modeling is made and a brief conclusion is presented.

MATERIALS AND METHODS

General description about TBM cutting tools and penetration

Almost exclusively, the methods that are used for rock excavation today employ either mechanical rock cutting tools or explosive charges. It is important, therefore, to have a good understanding of the advantages and the limitations of rock cutting with mechanical tools in order to assess both the potential for making significant technological advances using this approach and to develop a strategy for achieving these advances. Also, although many of the alternative methods for rock destruction, such as thermal or erosional, have been demonstrated as technically successful (that is, it is possible to excavate rock using these methods), most of these techniques are impractical either because they are extremely energy intensive, or they are not cost-effective. Hence, none of these alternative methods is likely to replace rock cutting with mechanical tools in the short-to-medium term (0 - 10 years).

Over the past two decades, full-face rock tunneling machines have become very widely used in mining and civil construction applications. A principal advantage is that this type of machine represents a quasi-continuous excavation system, compared with the alternative, cyclic, drill-and-blast method. Therefore, the tunnel advance rates generally are much greater when a TBM is employed. These machines can be used to drive circular tunnels in rock types that range from weak, loosely consolidated to very strong and abrasive. In almost all cases, breakage is affected by roller cutters mounted on the cutting head. Because these cutters break the rock by indentation, these machines are characterized by very high thrust requirements. This thrust is provided by hydraulic rams that press the cutterhead into the rock face. The thrust reaction force is reacted through gripper pads that are pressed, again hydraulically, against the tunnel walls. The rock broken from the face by the cutters falls to the floor where it is scooped into buckets mounted around the gage of the cutterhead. This debris is lifted in the buckets to the tunnel crown, whereupon it is tipped onto a belt conveyor that runs through the center of the machine. The most common type of cutting tool employed on these machines is the disc cutter. In some cases the cutting edge of this tool is a hardened steel surface (Figure 1), and in other cases it is a row of cemented tungsten carbide buttons that are press-fitted into the disc rim. The most common cross sections for a hardened steel disc cutter are wedge and constant section discs (Hartman, 1992).

The great majority of the rock cutting tools employed today are indenters. Thus all types of roller cutters -disc cutters, rolling cone bits, etc. - break the rock in an indentation process. Similarly, all types of percussive tools, including percussion drillbits, down-the-hole drillbits, and high-energy impact bits, induce rock fracture by indentation. As to disc cutters, many researchers have considered the cutting process as the indentation and some models have been developed for this process (Crow, 1975; Ozdemir et al., 1976; Roxborough and Phillips, 1975a; Roxborough and Phillips, 1975b; Lindqvist and Renman, 1980; Sanio, 1985). These researchers assumed a constant value for the indentation strength of a rock using a disc cutter. The area of the disc cutter in contact with the rock then can be calculated from considerations of the depth of rock penetration by the disc and the disc geometry. The product of this contact area at a given depth and the indentation strength then yields the thrust force acting on the disc. This approach as developed by Roxborough and Phillips (1975a, 1975b), is illustrated in Figure 2.

In current research, for feasibility study of presentation of a new technology, it is tried to consider the percussive loads in addition to conventional forces acting on disc cutters. For this purpose, mathematical modeling is employed to develop two different models for conventional and percussive status based on plasticity theory. The penetrations obtained from two analytical models are mathematically (and non-algebraic) summed together, and then the cumulative penetration caused by application of the new technology in hard rock TBMs is attained.

Analytical modeling

To understand the effect of appending the percussive force to conventional ones on TBM disc cutters, it is especially required, in the first step, to build an analytical model for penetration of simple indenter in a homogenous and isotropic rock medium. For this purpose, some assumptions are considered and then the amount of increase in penetration into the rock medium is analyzed using theory of plasticity. As the first assumption, type of indenter is assigned like a V-shaped tool. Primary scheme of constructed model for dual penetration in rock medium has been shown in Figure 3. As it is seen and understood, after regular penetration of indenter in the rock (h), the percussive load is applied and a supplementary penetration is made (h′).

The types of applied loads at two phases differ, and thus it is obligatory to consider different analytical models for each phase. At the first stage of the modeling process, a part of constructed model by Pariseau and Fairhurst (1967) for determination of tool penetration into rock considering friction between rock and tool is used. Then, the amount of penetration resulted from the impacts of a striker on the disc cutter is modeled by using the kinematic method. The aggregative penetration of the disc by application of rotary-percussive load is taken into account as summation of penetrations in two stages:

Penetration of V-shaped disc due to the conventional forces: In this section, the penetration of a disc cutter -assumed in form of a sharp wedge into a rock is considered to behave according to the equations of plasticity. Hill (1950) presented the governing equations of stress for a homogenous, isotropic weightless non-work-hardening material undergoing a slow plane-strain deformation. The equilibrium equations and the yield function were as follows:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = 0$$

$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = 0 \qquad (1)$$

$$Y(\sigma_{xx}, \sigma_{xy}, \sigma_{yy}) = 0 \qquad (2)$$

For rock-like materials which obey the Coulomb yield criterion, equation (2) may be written in the form:

$$\sigma_{xx}(\cos 2\theta - \sin\phi) - \sigma_{yy}(\cos 2\theta + \sin\phi) + 2\sigma_{xy}\sin 2\theta - 2c\cos\phi = 0 \qquad (3)$$

Where θ the angle is measured from the x-axis to the direction of the major principal stress, ϕ is the angle of internal friction of the material, and c is the cohesion. The usual Mohr diagram for a Coulomb material at yield is shown in Figure 4.

Letting:

$$1/2(\sigma_{xx} + \sigma_{yy}) + c\cot\phi = \sigma \qquad (3a)$$

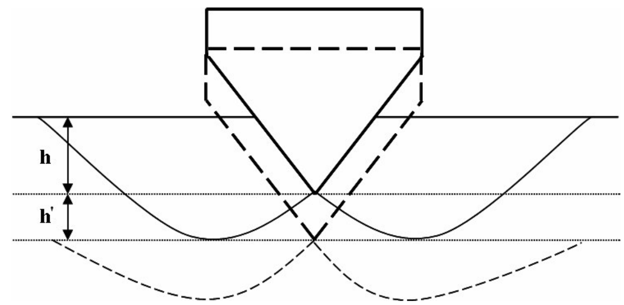

Figure 3. Scheme of the dual penetration for applying the new technology utilized in analytical modeling.

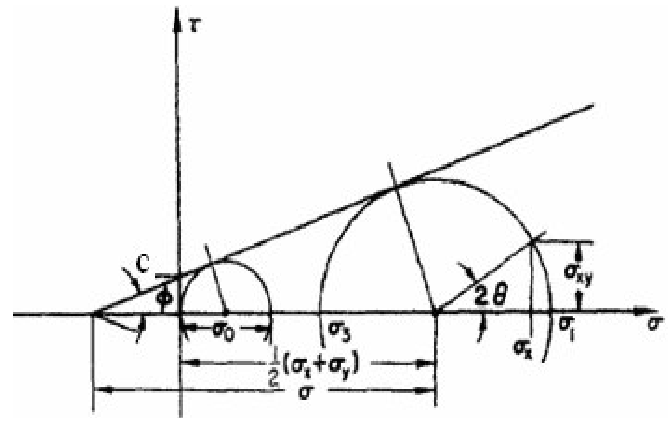

Figure 4. Mohr diagram for a Coulomb material at yield

σ is the generalized mean stress. Equations (1) and (3) can be transformed as has been described by Pariseau and Fairhurst (1967) into the system:

$$dy/dx = \tan(\theta \pm \alpha) \quad \text{(i)}$$

$$(1/2\cot\phi)(\ln\sigma) \pm \theta = \text{constants} \quad \text{(ii)} \qquad (4)$$

Where:

$$\alpha = \pi/4 - \phi/2. \qquad (5)$$

The two equations of (4i) define two sets of lines $y = f(x)$ known as the first and second families of failure surfaces or the sliplines. The two equations of (4ii) hold along the sliplines. The stress components σ_{xx}, σ_{xy} and σ_{yy} in the plastic region are given by the formulas obtained by substituting equation (3a) into equation (3) and using the result in the usual equations of transformation:

$$\sigma_{xx} = \sigma(1 + \sin\phi\cos 2\theta) - c\cot\phi$$

$$\sigma_{yy} = \sigma(1 - \sin\phi\cos 2\theta) - c\cot\phi$$

$$\sigma_{xy} = \sigma\sin\phi\sin 2\theta \qquad (6)$$

Ordinarily equations (4) cannot be integrated unless one can guess

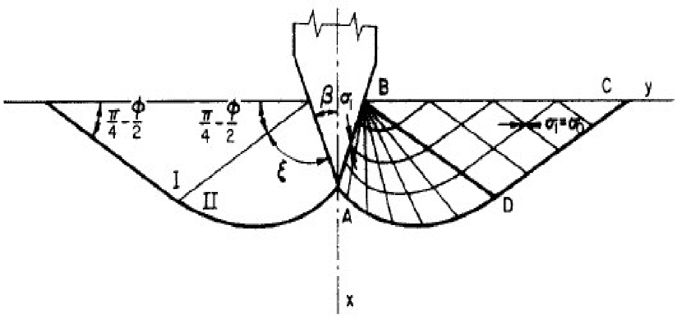

Figure 5. Assumed stress field for penetrated indenter (Pariseau and Fairhurst, 1967).

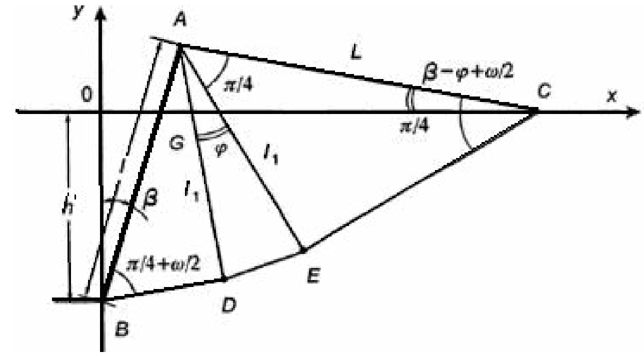

Figure 6. Strain pattern for penetration of the indenter into rock medium.

how θ varies along the sliplines. The more complete description about this issue and the current considered solution has been presented in Appendix A.

In this analysis, the width of the disc contact edge normal to the plane of the paper is b and is assumed to be constant and independent of depth of penetration. The rock is assumed to be in contact with the disc along the entire penetrated sides of the disc (Appendix B). Consider the situation in which friction along the disc-rock interface is such that the interface coincides with a failure plane. The interfacial shear stress (σ_{nt}) is effectively a maximum for a given value of σ_{tt}. The value of interface frictional coefficient is not required for the analysis; it is sufficient to specify the direction of the failure plane.

Consider Figure 5 in which the region I is uniformly at yield. The major principal stress is equal to the unconfined compressive strength. The angle θ equals $\alpha-\beta$. Successive computations of the stresses in the constant state region I and the constant state region adjacent to the disc (II) enable one to compute the stresses acting normal (σ_{nn}) and tangential (σ_{nt}) to the disc-rock interface (Pariseau and Fairhurst, 1967).

The resulting upward acting force, F is:

$$F = 2hb(\sigma_{nn}\tan\beta - \sigma_{nt}) \quad (7)$$

Substituting the equations for σ_{nn} and σ_{nt} in equation (6) we obtain the desired force-penetration characteristic for the disc, that is:

$$\frac{F}{bh\sigma_0} = \frac{\tan\beta}{\tan\phi\tan\alpha}\{[1+\sin\phi(\cot\beta\tan\alpha-1)]\exp(2\xi\tan\phi) - \tan^2\alpha\} \quad (8)$$

Where h is depth of penetration, β is disc half-wedge angle ($0 \le \beta \le \alpha$) and ξ is fan angle ($\xi = \pi/2 - \alpha + \beta$).

Using equation (8), it is possible to obtain the h value (depth of penetration) for specified conditions of acting force behind disc cutter.

Supplementary penetration due to the percussion behind the disc: Now the condition is assumed that the disc (indenter) has penetrated due to former forces to the depth that was analyzed in past section and then percussive energy is applied on the disc (Figure 3). In fact, impacts are acting on the V-shaped indenter, and consequently the depth of penetration will be increased. The rock under the impacts has been acted by former penetration and is really disturbed. So, it is required for modeling and analysis of this status, that the whole of effective rock medium would be assumed in the form of plastic region. For modeling purpose, the kinetic mechanism is considered.

By solving the problem of the penetration of a symmetric rigid wedge (with the angle at the vertex 2β) into a stiff-plastic medium with allowance for friction on the contact surface, it becomes possible to unambiguously determine the dependence of the degree of penetration of the indenter and the resistance force on the main parameters: the mass of the striker (m), initial velocity (v_o), lip angle of the wedge (2β), friction coefficient (μ) and number of impacts (k). Allowance is made for friction on the contact surfaces, and it is assumed that the indenter enters normally the half plane. The solution is constructed following the approach presented by Mochalov (1991) and Basheyev et al. (1999). In this case, the configuration of the plasticity region preserves the geometric similarity.

When penetrating the indenter, the medium is pressed out on its both sides. The strain pattern will have the form illustrated schematically in Figure 6. The medium in region ABDEC is in the plastic state. The boundary line AC is approximately by a straight line. The yield condition has the form:

$$(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2 = 4\tau_s^2 \quad (9)$$

Where τ_s is the yield point and the condition will be satisfied if:

$$\sigma_x = \sigma - \tau_s\sin(2\theta),$$
$$\sigma_y = \sigma - \tau_s\sin(2\theta),$$
$$\tau_{xy} = \tau_s\cos(2\theta) \quad (10)$$

Where σ is the mean pressure. Constructing the solution similarly to Mochalov (1991), the conditions on the boundary of the plasticity region are obtained.

On the face AB:

$$\sigma_n = p = -\tau_s(1+2\varphi) - \sqrt{\tau_s^{\ 2} - \tau_n^{\ 2}},$$

$$\tau_n = \mu p \ ; \ \omega = \arcsin(\tau_n / \tau_s) \ . \qquad (11)$$

On the straight line BD:

$$\sigma_n = \sigma_1 = -\tau_s(1+2\varphi),$$

$$\tau_n = -\tau_s \ . \qquad (12)$$

On the straight line EC:

$$\sigma_n = \sigma_2 = -\tau_s,$$

$$\tau_n = -\tau_s \ . \qquad (13)$$

On the arc DE:

$$\sigma_n = -\tau_s(1+2(\varphi-\alpha)), \ 0 \le \alpha \le \varphi,$$

$$\tau_n = -\tau_s \ . \qquad (14)$$

It is designated $|AB| = l$. Then the total force per unit of width of the indenter will be:

$$P = 2l(\sigma_n \sin\beta + \tau_n \cos\beta) = 2l\sigma_n \cos\beta(\tan\beta + \mu)$$
(15)

The parameter φ, which is yet to be determined, enters in the expressions for boundary conditions (11) - (14).

It is found from the geometry of the problem (Figure 6) that:

$$|AD| = |AE| = l_1 = l\sin\left(\frac{\pi}{4} + \frac{\omega}{2}\right)$$

$$|AC| = L = \sqrt{2}l_1 \qquad (16)$$

Thus, the position of point A on the indenter gives the condition:

$$l\cos\beta - h = \sqrt{2}l\sin\left(\frac{\pi}{4} + \frac{\omega}{2}\right)\sin\left(\beta - \varphi + \frac{\omega}{2}\right) \qquad (17)$$

Here, β and h are known. This relation therefore establishes the connection between l, φ and ω.

The fact that the medium is incompressible means that triangles OBG and GAC have the same area, which in turn leads to the expressions:

$$h^2\tan\beta = (l\cos\beta - h)\left[L\cos\left(\beta - \varphi + \frac{\omega}{2}\right) + (l\cos\beta - h)\tan\beta\right] \qquad 18)$$

Equations (11), (17) and (18) make it possible to find l and φ with given values of μ (or ω). Thus, boundary conditions (11) - (14) are completely determined, as is the form of the boundary of the plastic zone and the total force on the indenter (15).

With 2β and μ constant, the region of plastic yield changes in proportion to the value of h'. We will determine the value this quantity has during the operation of the tool. If the mass of the striker m is much greater that the mass of the rock in the plastic region, then the equation of motion of the tool is described with a high degree of accuracy by the simple expression:

$$m\ddot{h} = -P \qquad (19)$$

Where P is the value of resistance force to the motion of the tool and, in accordance with (15), is determined as:

$$P = 2b_0\bar{l}\sigma_n \cos\beta(\tan\beta + \mu)h' = P_0 h' \qquad (20)$$

Where b_0 is the width of the tool, $\bar{l} = l / h'$, $l = |AB|$, σ_n is the value of normal stress on AB-(1), μ is the friction coefficient, and h' is the value of the penetration of the tool. The solution of this equation, satisfying the initial conditions $h'(0) = 0$, $\dot{h}(0) = v_0$ (the initial velocity of the tool), will be:

$$h'(t) = \left(\frac{v_0}{z}\right)\sin(zt), \quad z^2 = \frac{P_0}{m} \qquad (21)$$

The time of motion of the tool to the stop $t_* = \pi / 2z$, while the final value of penetration after the first impact $h_1' = v_0 / z$. The value of l increases with the growth of h', and thus so does the force breaking the material. That force is determined as the projection of the forces from the face of the indenter AB onto 0x axis. By executing the necessary number of impacts, it will be possible to obtain sufficiently large values of the breaking forces. It is easily shown that for a constant initial tool velocity v_0, the value of penetration of the tool h_k' after the k th impact will be:

$$h_k' = \sqrt{k}h_1' = \sqrt{k}\frac{v_0}{z} \qquad (22)$$

Hereby, it is possible to calculate the penetration depth resulted from the supplementary percussive load on the indenter, in terms of the number of percussions.

Aggregative penetration resulting from the rotary-percussive loading: Now it is obviously requisite that the equation of aggregative penetration can be presented regarding the previous assumptions and models settings. The preliminary depth of penetration due to the conventional forces can be calculated from equation (8):

$$h = \frac{F.(\tan\phi \tan\alpha)}{b\sigma_0 \tan\beta\{[1+\sin\phi(\cot\beta\tan\alpha - 1)]\exp(2\xi\tan\phi) - \tan^2\alpha\}} \quad (23)$$

As the basic assumption in this research, it has been defined that firstly the indenter would penetrate to the depth of h and then a percussive load would cause more penetration to the depth of h' (Figure 3). In this situation, the cumulative depth of penetration (h_t) will be $h + h'$. Thus it is necessary that the number of percussions to penetrate to the depth of h would be determined. Let us suppose k_0 as the required percussions to penetrate to the preliminary depth of h (without any percussion) and also k as the required percussions to penetrate to the depth of h'. Thus we can say $h = \sqrt{k_0}\frac{v_0}{z}$, and then we can find:

$$k_0 = \left[h\left(\frac{1}{(v_0/z)}\right)\right]^2 \quad (24)$$

Here as the final concept, h'_k means the depth of penetration due to k percussions after fulfillment of penetration of the disc cutter caused by the conventional forces (h). This depth also can be represented by h'_{k_0}. Therefore, the cumulative depth of penetration aggregated from the conventional and percussive forces would be h'_{k_0+k}. Now it is concluded that:

$$h'_k = h'_{k_0+k} - h'_{k_0}$$

$$h'_k = \sqrt{k_0 + k}\left(\frac{v_0}{z}\right) - \sqrt{k_0}\left(\frac{v_0}{z}\right)$$

$$h'_k = \sqrt{\left(\frac{hz}{v_0}\right)^2 + k}\left(\frac{v_0}{z}\right) - \sqrt{\left(\frac{hz}{v_0}\right)^2}\left(\frac{v_0}{z}\right)$$

$$h'_k = \sqrt{\left(\frac{hz}{v_0}\right)^2 + k}\left(\frac{v_0}{z}\right) - h \quad (25)$$

And then as the final:

$$h'_k = \left[\sqrt{h^2 + \left(\frac{v_0}{z}\right)^2 k}\right] - h \quad (26)$$

As it is seen from equation (26), it is simply possible to calculate the depth of penetration due to k percussions after penetration of the disc to the depth of h (note that inputs and outputs of penetration values in this equation have to be in centimeters rather than meter).

The nature of the presented rotary-percussive concept dictates that at first the depth of h would be excavated by conventional compressive and rotary loads of disc and then k numbers of percussions would act on the disc for penetration to the supplementary depth of h'_k. In the last sections, all of these issues and the related formulae were presented based on each proper theory and analytic modeling.

With regard to the above, the final aggregative relations could be derived as equations (27).

$$h_t = h + h'_k \Rightarrow$$

$$\begin{cases} h = \dfrac{F.(\tan\phi\tan\alpha)}{b\sigma_0\tan\beta\{[1+\sin\phi(\cot\beta\tan\alpha-1)]\exp(2\xi\tan\phi)-\tan^2\alpha\}} \\ h'_k = \left[\sqrt{h^2 + \left(\dfrac{v_0}{z}\right)^2 k}\right] - h \end{cases} \quad (27)$$

These relations can properly calculate and estimate the depth of penetration of a single disc cutter in a rock medium resulted from its rotation, compression and also subsequent percussion behind it.

EXAMPLE

In this section, a typical example is presented to show how the analytical results of this study can be used in the real applications. Consider a situation in which a single disc cutter penetrates in a hard rock and then a percussion acts on it to the more penetration. The parameters are given below:

$\beta = 15$;

$\phi = 36$, $\alpha = \pi/4 - \phi/2$ =27;

$\xi = \pi/2 - \alpha + \beta = 78$;

$\mu = \tan\phi = 0.726$;

$d = 18\,cm = 0.18\,m$;

$F = 10\,ton.f = 98100\,N$;

$\sigma_0 = 40\,MPa = 40000000\,N/m^2$;

$$h = \frac{F.(\tan\phi\tan\alpha)}{b\sigma_0\tan\beta\{[1+\sin\phi(\cot\beta\tan\alpha-1)]\exp(2\xi\tan\phi)-\tan^2\alpha\}} = \frac{36315.826}{b\times 112831171.223}$$

After 4 iterations (Appendix B):

$$b = 0.0608\,m$$

And

$$h = 0.00529\,m = 5.29\,mm$$

Thus the penetration due to the conventional forces on the disc would be 5.29 mm according to the given conditions. The parameters for percussion on the disc are:

$$m = 20\,kg = 196.2\,N\ ;$$

$$\nu_0 = 4\,m/\sec\ ;$$

$$z^2 = \frac{P_0}{m} = \frac{5417.008}{196.2} = 27.609$$

$$h'_k = \left[\sqrt{h^2 + \left(\frac{\nu_0}{z}\right)^2 k}\,\right] - h = 0.927 - 0.529 = 0.398\,cm = 3.98\,mm$$

Thus the percussion generates 3.98 mm further penetration. The aggregative depth of penetration for the disc would be:

$$h_t = h + h'_k = 5.29 + 3.98 = 9.27\,mm$$

It is worth to note that this depth is of a single cycle by a single disc cutter for the given conditions. Certainly, in real world, the more numbers of percussion would result the higher penetration by multiple discs on the rock.

Discussion and conclusion

Generally, the increase in amount of penetration into rock, and consequently in rock fragmentation and advance rate, is one of the most major aims in every tunneling project, and especially in excavations by TBM. To approach this goal, many efforts have been done in the past, and thus numerous researchers have worked on the ways to increase the penetration. Moreover, finding ways towards reduction of consumed power in such projects is so remarkable. For this purpose, it is requisite that the need of the machine to thrust would be reduced to such a degree that this reduction would not overshadow the rock fragmentation and advance rate of TBM. As it is understood, these two goals are in opposite sides and achieving both is not probably possible by the common existing methods. Therefore, the new rotary-percussive technology has been defined; and at the first step, the solution has been considered from the analytical point of view.

As it was seen in former sections, the increase in the penetration by using the supplementary percussive load behind the disc cutters is imminent. The dual penetration scheme (Figure 3) and also performed modeling in Section 2 approve this statement. In fact, the depth of penetration resulted from application of rotary-percussive load equals with the summation of depths of two different types of penetration. This phenomenon can be more illustrated from the force-time viewpoint. During continuous boring in the field, (Zhang, 2004) showed the normal force of a disc cutter measured in various time steps. Assumption of its combination with a supposed ordinary percussive load during the machine's work can help to further understanding and believing the authors claim about the significance of appending supplementary dynamic loads to the cutters.

Moreover, it should be taken into account that since the percussive load is of dynamic type, it might be simply able to cause to form the cracks and also quickly increase the length of previous formed cracks. As a result, the supplementary load would cause to increase the amount of rock fragmentation under disc cutter.

In this paper, the effect of appending a supplementary percussive load to the rotary energy of TBM disc cutters was analytically investigated. Two analytical models were built to predict the amount of penetration of a disc cutter assumed in form of a V-shaped tool in rock medium. At first stage of the modeling process, part of a previously constructed model by for determination of tool penetration into rock considering friction between rock and tool was utilized. Then, at the subsequent stage, the amount of penetration resulted from the impacts of a striker on the disc cutter was modeled by using the kinematic method. The aggregative penetration of the disc by application of rotary-percussive load was considered as summation of the penetrations in two stages by acting the mathematical substitutions. Finally, an example was presented to verify the derived formulae and show how these relations can be applied in the real situations.

This research was accomplished as the first part of a great project for presentation of the new rotary-percussive technology applicable in TBMs, which is carrying out in Rock Mechanics Laboratory of Shahrood University of Technology, Iran. Numerical modeling and experimental and laboratorial studies are requisite for completion of the presented theory. Afterwards, it is possible to investigate about the construction conditions of such a technology and formalize the rotary-percussive TBMs.

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Appendix A

Description about θ and related equations

Two useful cases that are frequently used arise whenever θ is constant along one or both families of sliplines. If θ is constant along both sliplines then, integrating (4i) we find:

$$y = x\tan(\theta \pm \mu) + \text{constant}$$

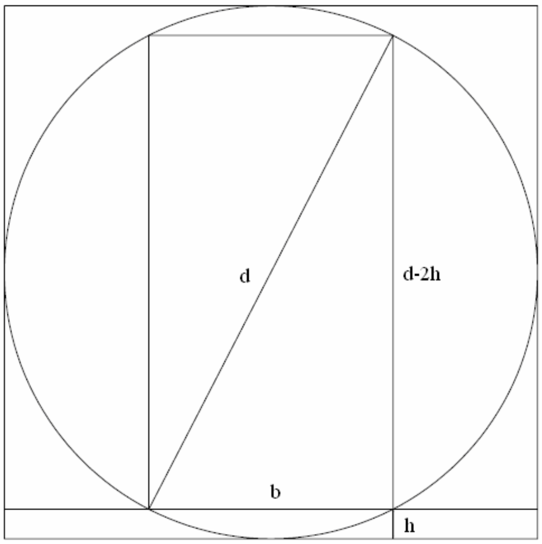

Figure B-1. Geometry of disc, depth pf of penetration and disc width

That is the sliplines are straight and intersect at an angle of $\pi/2-\phi$. Since in this case log σ is constant, i.e. σ is constant, the stresses are constant throughout the region, which is therefore a "constant state region".

If θ is constant along one family of sliplines then it may be shown that the order family is composed of exponential spirals. Equations (4) are then more appropriately expressed in polar co-ordinates (r, ω) in the form:

$$\omega = \text{constant}$$
$$\left(\frac{r}{r_0}\right) = \exp[(\omega-\omega_0)\tan\phi]$$
$$\sigma = \text{constant}$$
$$\left(\frac{r}{r_0}\right) = \exp[-2(\omega-\omega_0)\tan\phi] \quad \text{(A-1)}$$

The resulting stress field is often referred to as a "region of radial shear", in reference to the fact that the family of straight sliplines (ω=constant) pass through a common point to form a "centered fan".

The stress fields corresponding to constant state and radial shear regions may be used to estimate the force-penetration characteristics of V-shaped disc cutters penetrating a Coulomb plastic rock mass.

Appendix B

Parameter b (indenter width) normal to the paper plane The disc cutter can be considered to be penetrated to depth h in rock medium. Then parameter b that is used in depth calculation formulae would be modeled geometrically like as shown here in Figure B-1 and can be calculated by a few iterations in terms of preliminary parameter h.

$$b=\sqrt{d^2-(d-2h)^2} \quad \text{(B-1)}$$

REFERENCES

Basheyev GV, Yefimov VP, Martynyuf PA (1999). Formation of an incipient crack in the impact fracture of a brittle body by a wedge. J. Min. Sci. 35(1): 51-58.
Cook NGW, Hood M, Tsai F (1984). Observation of crack growth in hard rock loaded by an indenter. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 21: 97-104.
Crow SC (1975). Jet Tunneling machines: a guide for design. Tunn. Tunneling March: 23-38.
Gertsch R, Gertsch L, Rostami J (2007). Disc cutting tests in Colorado Red Granite: Implications for TBM performance prediction. Int. J. Rock Mech. Min. Sci. 44: 238-346.
Gong QM, Zhao J, Henfy AM (2006). Numerical simulation of rock fragmentation process induced by two TBM cutters and cutter spacing optimization. Tunneling and Undergr. Space Technol 21(3-4): 263.
Gong QM, Zhao J, Jiao YY (2005). Numerical modeling of the effects of joint orientation on rock fragmentation by TBM cutters. Tunneling and Undergr. Space Technol. 20: 183-191.
Hartman HL (1992). SME Mining Engineering Handbook. Second edition, Vol. 1, Society for Mining, Metallurgy, and Exploration, Inc. Littleton, Colorado.
Hill R (1950). Mathematical theory of plasticity. Clarendon Press, Oxford.
Hood M and Alehossein H (2000). A development in rock cutting technology. Int. J. Rock Mech. Min. Sci. 37: 297-305.
Innaurato N, Oggeri C, Oreste PP, Vinai R (2006). Experimental and Numerical Studies on Rock Breaking with TBM Tools under High Stress Confinement. Rock Mech. Rock Eng. 40(5): 429-451.
Knickmeyer W, Bauman L (1981). Activated Roller Cutters as a Means of Rock Breakage Initial Test Results and Future Applications. In: Proceedings of Rapid Excavation and Tunneling Conference, San Francisco, California, Chapter 83.
Kou SQ (1995). Some basic problems in rock breakage by blasting and by indentation. Ph.D. Thesis: 180D, Lulea University of Technology, Lulea, Sweden.
Kou SQ, Liu HY, Lindqvist PA, Tang CA (2004). Rock fragmentation mechanisms induced by a drill bit. Int. J. Rock Mech. Min. Sci. 41(1): 527-532.
Li XS, Hood M, Rowlands J (1999). Oscillating disc cutter- effect of rock properties. In: Proceedings of 5th International Symposium on Mine Mechanization and Automation, Sudbury, Ontario, Canada.
Lindqvist PA (1982). Rock fragmentation by indentation and disc cutting. Ph.D. Thesis: 20 D, University of Lulea, Lulea, Sweden.
Lindqvist PA, Ranman KE (1980). Mechanical rock fragmentation chipping under a disc cutter. Technical Report 59T, University of Lulea, Lulea, Sweden.
Lindqvist PA, Suarez del Rio LM, Montoto M, Tan XC, Kou SQ (1994). Rock indentation database. SKB Project Report, PR-44-94-023.
Liu HY (2003). Numerical modeling of the rock fracture process under mechanical loading. Licentiate Thesis: 04 L, Lulea University of Technology, Lulea, Sweden.
Mochalov EA (1991). Mathematical description of the introduction of the tool of a percussive machine into a material being fractured. Fiz.-Tekh. Probl. Razrab. Polezn. Iskop. No. 6.
Nishimatsu Y (1972). The mechanics of rock cutting. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 9: 261-270.
Ozdemir L, Miller R, Wang F (1976). Mechanical tunnel boring prediction and machine design. Annual Report, Colorado School of Mines, Golden, CO.

Pariseau WG, Fairhurst C (1967). The force-penetration characteristic for wedge penetration into rock. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 4: 165-180.

Roxborough FF, Phillips HR (1975a). The mechanical properties and cutting characteristics of the Bunter Sandstone. Report, Transport and Road Research Laboratory, Crowthorne, UK.

Roxborough FF, Phillips HR (1975b). Rock excavation by disc cutter. Int. J. Rock Mech. Min. Sci. Geomech. Abst. 12(12): 361-366.

Sanio HP (1985). Prediction of the Performance of Disc Cutters in Anisotropic Rock, Int. J. Rock Mech. Min. Sci. Geomech. Abst. 3: 153-161.

Swoboda G and Abu-Krisha A (1999). Three-dimensional numerical modeling for TBM tunneling in consolidated clay. Tunneling Undergr. Space Technol. 14(2): 327-333.

Swoboda G, Kenawi MA, Ramadan EH (2004). Numerical investigation of TBM tunneling in consolidated clay. Tunneling Undergr. Space Technol. 19: 459.

Zhang ZX (2004). Estimate of loading rate for a TBM machine based on measured cutter forces. Rock Mech. Rock Eng. 37(3): 239-248.