NUMERICAL SIMULATION OF ROCK CUTTABILITY

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ABSTRACT: Cuttability of rocks is an inevitable factor in order to predict the excavation performance of a mining machine. It is estimated by defining the cutting forces acting on a cutter. This paper mainly describes the ways of determination of the rock cuttability. It is done by several ways. The first way is the calculation from theoretical methods which are based on some assumptions and empirical approaches. In addition, it is measured from laboratory cutting experiments. Another way is to simulate the cutting process by utilizing some numerical codes or computer aided programs. In the scope of this paper, all these methods have been investigated and one of the modeling studies (in PFC^{3D}) of the authors is presented.

Keywords: Cuttability; PFC^{3D}; Linear cutting set

1. INTRODUCTION

The necessity of underground transportation system has been rapidly increasing with the growing population of the world. The railway and metro tunnels have been extensively opening everyday through various ground conditions. Roadheaders and the full scale tunnel boring machines (TBM) are some of the mechanized machines commonly employed for underground excavations. These machines should work on both soft and hard rocks. Hence, the ground conditions, which have a fundamental impact on machine selection, should be investigated precisely before opening a tunnel.

The uniaxial compressive strength of the rock is the dominant parameter influencing the machine performance. In addition, the geological parameters, machine parameters, and operation and maintenance parameters determine the excavation performance of the machine as shown in Figure 1 [1]. With respect to these parameters, cutting performance is also evaluated by utilizing the cuttability property of rock.

Generally, the methods employed to determine the cuttability involve:

- The cutting of rock with a high strength metal (cutter) such as tungsten carbide.
- Measuring the forces on the cutting tool or the volume of rock excavated.
- An assessment of the abrasivity of the rock by measuring the wearing rate of the cutting tool [2].

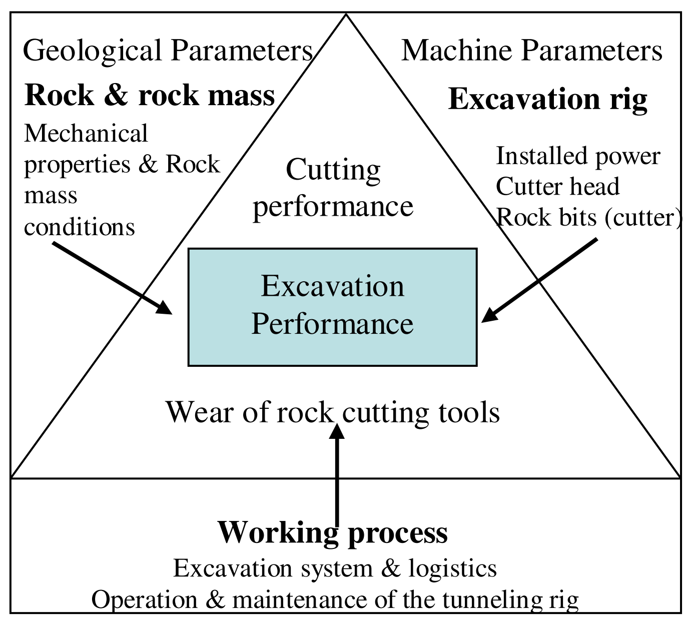

Fig. 1. The parameters influencing the excavation performance [1].

There are a number of tests available to measure cuttability of rock. Some of them are uniaxial compressive strength, tensile strength, Schmidt hardness, Shore hardness, quartz content of rock, impact strength index, cone indenter index, laboratory cutting tests, and etc. Laboratory cutting test is the most reliable one among these tests. It is basically carried out in the linear cutting sets. The relieved and unrelieved cutting tests are performed in those sets and the cutting forces recorded from these tests provide information about the cuttability.

Besides, there are also a few researchers who have investigated the analytical solutions of cutting forces in last decades. Depending on the cutter used, many cutting theories have been improved.

In addition, there are computer aided programs and numerical methods which can analyze, interpret and simulate the cutting process depending on the cutting parameters. These numerical methods essentially consist of continuous and discontinuous methods. Discontinuous methods are more convenient due to capability of modeling the jointed rock and rock masses. In this paper, some of the applications of these methods are introduced.

2. CUTTABILITY OF ROCKS

Investigation of the rock cuttability is the most important process in the course of performance prediction of a mining machine. The cuttability is basically described by evaluating the cutting forces on the cutting tool. These forces are estimated by different ways. These are:

- Rock cutting theories,
- Laboratory cutting experiments,
- Simulation of cutting process.

2.1. The Cutting Theories

The cutting theories were developed by different researchers in order to describe the process of chip formation and calculate the cutting forces acting on a cutter. They are determined by theoretical and analytic solutions (models) which are based upon some assumptions and experimental observations.

The first cutting theory was proposed by Merchant [3]. It was applied for the metal cutting. Then, Evans [4] presented a rock cutting theory for both chisel and point attack tools as given in Eqs. (1-2). Another theory which is similar to Merchant's shear model was proposed by Nishimatsu [5] for rock cutting of conical cutters as given in Eq. (3). Roxborough and Philips [6] developed a theory for disc cutters. Goktan [7] modified Evans' theory for point attack cutters as given in Eq. (4).

$$FC = \frac{2\,\sigma_t\; d\; w\; Sin\frac{1}{2}\left(\frac{\pi}{2} - \alpha\right)}{1 - Sin\frac{1}{2}\left(\frac{\pi}{2} - \alpha\right)} \tag{1}$$

$$FC = \frac{16\,\pi}{Cos^2\theta}\left(\frac{\sigma_t}{\sigma_c}\right)\sigma_t\; d^2 \tag{2}$$

$$FC = \frac{2}{n+1} S_s d \frac{Cos(k)}{1 - Sin\left(k - \alpha + \phi\right)} \tag{3}$$

$$FC = \frac{4\Pi\sigma_t d^2\; Sin^2(\theta+\psi)}{Cos\;(\theta+\psi)} \tag{4}$$

In eqs. (1) through (4), FC, σ_t, d, w, α, θ, σ_c, n, S_s, k, Φ and ψ denote respectively, cutting force, uniaxial tensile strength, depth of cut, tool width, rake angle, half of tip angle, uniaxial compressive strength, the stress distribution factor, the shear strength, the angle of internal friction, the angle of friction of rock cutting and, friction angle between cutter and rock.

However, the most comprehensive and accepted theories are those of Evans' for chisel picks and conical picks and of Nishimatsu's for chisel picks. A more detailed description of cutting theories can be found in Bilgin et al. [8].

2.2. Linear Cutting Set

The cutting forces can also be obtained from laboratory rock cutting experiments. The tool-rock interaction is taken into consideration by performing the test in the laboratory. This is the most powerful and practical method applied nowadays. It is widely accepted and inevitable test method for the performance prediction of a mining machine.

The cutting tests are conducted in particularly designed cutting sets. The first rock cutting set was originally developed by the Colorado School of Mines [9]. The one, which was designed and manufactured within the NATO-TU excavation project, in Istanbul Technical University is shown in Figure 2.

The relieved and unrelieved mode of rock cutting is carried out in this set. Chisel, point attack and disc cutters are employed. Some of the cutting parameters such as depth of cut, line spacing can be changed during the test. The other cutting parameters such as attack angle, cutting speed, and tilt angle are chosen as constants [10].

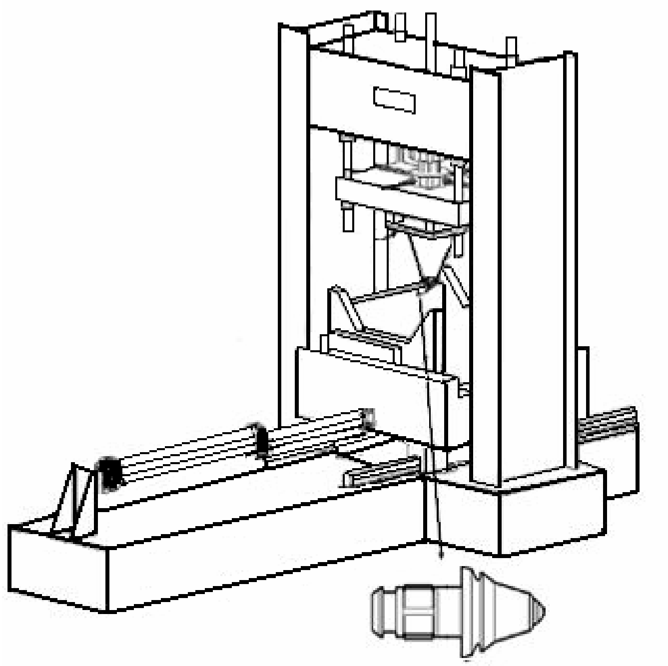

Fig. 2. Schematic view of full scale linear cutting set [10].

2.3. Numerical Modeling of Rock Cuttability

Underground excavation design, crack growth, damage in the rock, tool-rock interaction, calculation of the cutting forces acting on the cutter can be visualized and simulated by computer aided programs or numerical codes. Examine^{2D}, Examine^{3D}, FRANC2D/L, NASGRO, and R-T^{2D} (rock and tool interaction) can be given as examples of such computer aided programs.

Also, there are some codes which have been based on numerical methods. Finite element method (FEM), finite difference method (FDM), and discrete element method (DEM) may be the most commonly applied ones. However, discrete element method has the best potential for studying the behavior of rock cutting since the rock specimen has a heterogeneous structure. It is originally proposed by Cundall and Strack [11] to analyze a collection of granular particles. The codes such as FLAC^{2D}, FLAC^{3D} employ finite difference method while PFC^{2D} and PFC^{3D} employ discrete element method. However, both PFC^{2D} and PFC^{3D} need to be calibrated for micromechanical properties before they are used for rock cutting simulations. One of the earlier suggestions of the calibration process can be found in Kulatilake et al. [12]. Then, it was adopted by other users.

All these programs and codes have the capability of modeling the tool-rock interaction. Some of the applications of these programs and codes are given below.

3. NUMERICAL MODELING STUDIES

Due to theoretical difficulties, empirical assumptions and the time loss in laboratories, cuttability of rock has been modeled by different researchers. The cutting forces were monitored in those modeling studies.

Huang [13] was the first to model rock cutting experiment by using PFC^{2D}. The main objective of Huang's research was to establish whether the occurrence of the failure modes (ductile at small depth of cut, brittle at large depth) observed in rock cutting experiments could be duplicated in numerical simulations. Then, it was found that the transition between ductile and brittle failure modes depends on the depth of cut. Additionally, longer cutting length was needed to extract more reliable average forces.

Lei and Kaitkay [14] then simulated the rock cutting to study the effect of hydrostatic pressure during the simulation (Fig. 3). The simulation results showed an increase in cutting force with hydrostatic pressure.

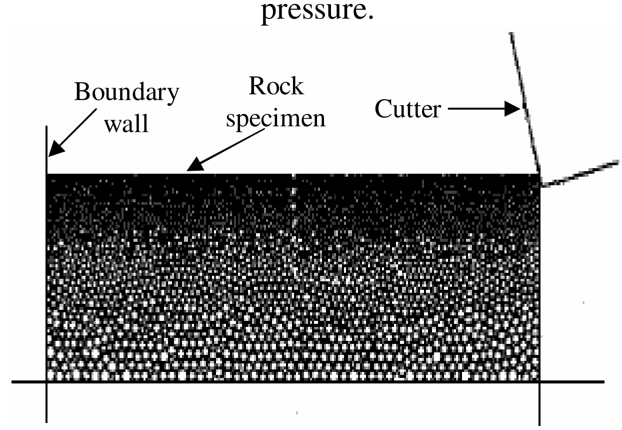

Fig. 3. A brittle mode of rock cutting test [14].

Stavropoulou [15] simulated the cutting process both in PFC^{2D} and FLAC by moving the cutter horizontally to the right at a relatively low velocity to approximate quasi-static loading conditions, and in plane strain conditions (Figs. 4-5). The main purpose of the study was to examine how the rock-cutting experimental results would be reproduced by numerical or analytical model results. During the simulations exerted forces on the cutter, damage that was depicted by the intensity, location and orientation of the microcracks, and force distribution within the granular model were monitored.

A FLAC^{2D} simulation, cutting as a steady-state process and PFC^{2D} simulation, cutting as a destructive process, showed a good agreement with the experimental data [15].

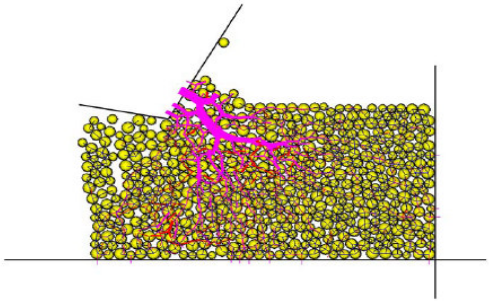

Fig. 4. Distribution of contact forces and particle bonds [15].

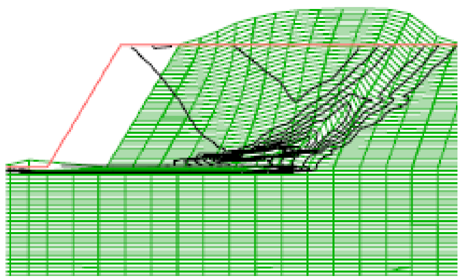

Fig. 5. Cutting simulation with FLAC^{2D} [15].

Another simulation, which is the only one carried out in three dimensions in the literature, was performed by Su and Akcin [16] in order to assist performance prediction of a mining machine. For this purpose, unrelieved rock cutting test was simulated by using a conical cutter in PFC^{3D}. The modeling studies were carried out on a sandstone rock having 7.5*7.5*7.5 mm in dimensions and 3 mm of depth of cut. During the simulations, confining pressure was applied in order to prevent the boundary particles from flying away. After the simulations, the variation of the cutting forces versus cutting distance was plotted and the effect of the confining pressure was investigated. The best agreement between laboratory and modeling studies was presented. The schematic view of the specimen and the cutter is given in Fig 6.

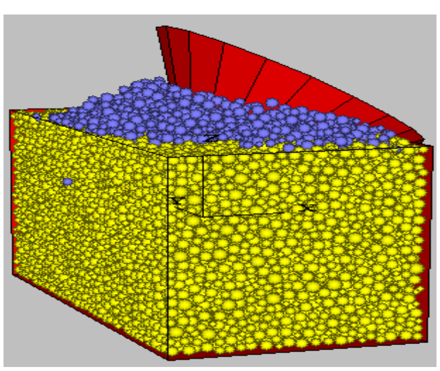

Fig. 6. The front view of the specimen and the cutter [16].

Jonak and Podgorski [17] examined the layer of the crushed material formed in the vicinity of the cutter during the simulation of the rock cutting process. Different combinations of elasticity and plasticity states were analyzed for the layer and rock. The simulations were performed by means of finite element method as shown in Fig 7. The causes of possible wear of the cutting edge were established as a result.

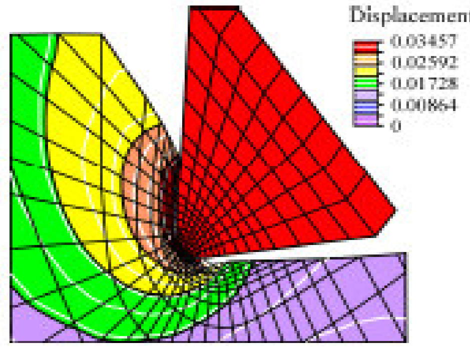

Fig. 7. Field of displacements of plastic layer and the rock [17]

Liu et al. [18] developed R-T^{2D} (Rock and Tool interaction), based on the rock failure process analysis model, to simulate the fracture process in cutting heterogeneous brittle material (Fig 8).

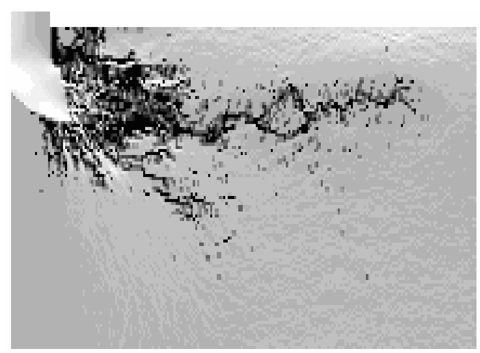

Fig. 8. Fracture process in cutting (maximum stress distribution) [18].

The simulated results reproduced all of the fragmentation processes in rock cutting such as the build-up of the stress field, the formation of the crushed zone, surface chipping, crater formation and the formation of subsurface cracks. It was also found that there were some peculiarities in cutting heterogeneous brittle materials.

According to another research carried out by Rojek [19], discrete element modeling of rock cutting was simulated (Fig. 9). He used his own discrete element implementation within Simpac code developed in CIMNE (Barcelona). In the modeling studies, Evans and Nishimatsu's cutting theories were solved mathematically and the simulation of the failure mode was attempted. Then, he matched the results of both studies and discovered a good agreement between them.

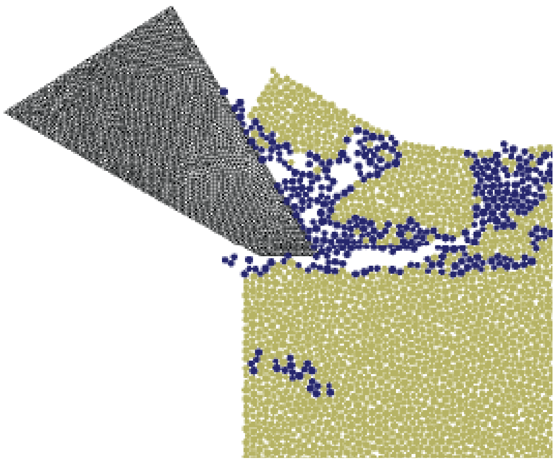

Fig. 9. Failure mode during rock cutting [19].

Some of other reviews of numerical simulation of the rock cutting process can be found in Liu et al. [18] and Kou et al. [20].

4. CONCLUSIONS

Although rock mass is a complicated material with joints, discontinuities, faults, and heterogeneities, numerical modeling methods have been used to simulate the behavior of rock mass. One of the behaviors encountered is the fracture propagation which is a result of rock cutting process using a cutter.

Rock cutting by pick (cutter) action involves the movement of the tip, taking a given depth, into the material being cut until the force generated by the pick exceeds the resistance to failure by cutting of that material. The result is the formation of a chip released from the parent block. Records of cutting force for a wide variety of brittle materials all indicate a general tendency for cutting force to gradually build up to a peak value and then to rapidly fall as the chip is formed [21].

The records of the cutting forces provide information about the cuttability of rock. It is the main and the most important parameter in the selection of appropriate excavation machine for the formation. Therefore, it is necessary to consider determination of the cuttability for excavation machines used underground.

Many researchers have investigated theoretical solutions of the cutting forces since 1945. In addition, a linear cutting test rig has been developed and employed for the last 20 years in order to measure cutting forces. However, with the advancement of the computer technology, the numerical codes play an important role in the prediction of the cutting forces and other areas.

In this paper, the theoretical models proposed by different scientists were discussed first. Then, the linear cutting test rig was introduced. Finally, the numerical models developed by some researchers regarding cuttability of rocks were presented. Also, the cutting model which was developed by the authors was also mentioned.

In the light of modeling studies presented above, it is seen that discrete element method has the best capability in order to model rock cutting process. Thus, the main research subjects of rock cuttability such as tool-rock interaction, measurement of cutting forces, crack propagation, and etc. are better simulated with discrete element method in comparison with other numerical methods.

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REFERENCES

1. Thuro, K. and Plinninger, R.J. (1999) Roadheader excavation performance – geological and geotechnical influences, In *Proceedings of the 9th ISRM Congress, Paris, 25-28 August 1990,* eds. Vouille, G. and Berest, P., 1241-1244. Rotterdam, Brookfield : Balkema.
2. Smith, I.M. (1975) *Correlation of rock properties and tunnel machine performance in selected sedimentary rock*, Ph.D. thesis, University of Newcastle upon Tyne, U.K.
3. Merchant, M.E. (1945) Basic mechanics of the metal cutting process., *J. Appl. Mech.*, **66** : 168-175.
4. Evans, I. (1962) A theory of the basic mechanics of coal ploughing, In *Proceedings International Symposium on Mining Research,* **2**: 761-798, Pergamon Press, London.

5. Nishimatsu, Y. (1972) The mechanics of rock cutting, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **9**: 261-270.

6. Roxborough, F.F. and Philips, H.R. (1975) Rock excavation by disc cutter, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **12** : 361-366.

7. Goktan, R.M. (1997) A suggested improvement on Evans' cutting theory for conical bits, In *Proc. 4th Int. Symposium on Mine Mechanization Automation*, **1**: A4-57/61, Brisbane, Australia.

8. Bilgin, N., Demircin, M.A., Copur, H., Balci, C., Tuncdemir, H. and Akcin, N.A. (2006) Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results, *Int. J. Rock Mech. & Mining Sci*., **43**: 139-156.

9. Chang, S.H., Soon, W.C., Gyu, J.B. and Seokwon, J. (2006) Performance prediction of TBM disc cutting on granitic rock by the linear cutting test, *Tunneling and Underground Space Technology*, **21** (3-4) :271-277.

10. Balci, C. and Bilgin, N. (2007) Correlative study of linear small and full-scale rock cutting tests to select mechanized excavation machines, *Int. J. of Rock Mech. & Mining Sciences*, **44**: 468-476.

11. Cundall, P.A. and Strack, O.D.L. (1979) A discrete numerical model for granular assemblies, *Geotechnique*, 29 (1) : 47-65.

12. Kulatilake, P.H.S.W., Malama, B. and Wang, J. (2001) Physical and particle flow modeling of jointed rock block behavior under uniaxial loading, *International Journal of Rock Mechanics & Mining Sciences*, **38** : 641-657.

13. Huang, H., Detournay, E. and Bellier, B. (1999) Discrete element modelling of rock cutting. In *Rock Mechanics for Industry*, eds. Amadei, Kranz, Scott & Smeallie, 123-130, Rotterdam: Balkema.

14. Lei, S.T. and Kaitkay, P. (2003) Distinct element modeling of rock cutting under hydrostatic pressure, *Key Engineering Materials*, **250** : 110-117.

15. Stavropoulou, M. (2006) Modeling of small-diameter rotary drilling tests on marbles, *Int. J. of Rock Mech. & Mining Sciences*, **43** (7) : 1034–1051.

16. Su, O. and Akcin, N.A. (2008) Modeling of unrelieved rock cutting test by using PFC^{3D}, In Proc. of 1st International FLAC/DEM Symposium on Numerical Modeling, 24-27 August 2008, eds. R. Hart, C. Detournay & Cundall, 165-172, Minneapolis, MN, USA.

17. Jonak, J. and Podgorski, J. (2001) Mathematical model and results of rock cutting modeling, *Journal of Mining Science*, **37** (6) : 615-618.

18. Liu, H.Y., Kou, S.Q. and Lindqvist, P.A. (2002) Numerical simulation of the fracture process in cutting heterogeneous brittle material, *International Journal for Numerical and Analytical Methods in Geomechanics*, **26**:1253–1278.

19. Rojek, J. (2007) Discrete element modeling of rock cutting, *Computer Methods in Material Science*, **7**(2):224-230.

20. Kou, S.Q., Lindqvist, P.A., Tang, C.A. and Xu, X.H. (1999) Numerical simulation of the cutting of inhomogeneous rocks, *International Journal of Rock Mechanics and Mining Sciences*, **36** :711-717.

21. Whittaker, B.N. and Szwilski, A.B. (1973) Rock cutting by impact action, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, **10** : 656-671.