

Optimization of TBM Performance Using Force-Penetration Interaction Diagram for Hard Rock

Ebrahim Farrokh¹

¹Mining engineering faculty, Amirkabir university of technology (Tehran polytechnic)

ABSTRACT

In the phase of the design of a TBM, it is essential to optimize the cutterhead characteristics with respect to cut and cutter geometry parameters in order to maximize both cutter penetration and TBM advance rate. In this regard, valuable results have been achieved from numerical simulations and laboratory tests, however due to presence of some shortcomings for such methods (e.g. high difference between rolling force measured in laboratory and actual field data), there is a high demand by the industry to conduct actual field data analyses. So far, very few efforts have been made to study the optimum cutter performance (e.g. penetration, normal force, and rolling force) based on the information of completed tunnel projects from around the world. To investigate the influence of various parameters on the cutter penetration and to provide basic guideline for the evaluation of the optimum TBM performance in hard rock conditions, an extensive field database is compiled.

On the basis of the data analysis of this database, it is found that the linear speed of the cutters has a direct correlation with two major parameters of normal force index (NFI) and rolling force index (RFI). In this regard, two formulas are generated using statistical analysis of the data from around 260 tunnel projects to evaluate both NFI and RFI. The corresponding formulas have coefficient of determination of 77 and 68% respectively. These formulas are used in an optimization process to maximize cutter penetration using the interaction of various operational constrains (cutter load capacity, cutterhead torque limit, cutter geometry constrains, and cutterhead penetration rate limits). The produced interaction diagram is called force-penetration interaction diagram. The new findings of this study can provide a foundation to improve the design process of hard rock TBMs and to optimize their performance considering various project setting parameters.

KEYWORDS

Optimization, TBM performance, interaction diagram, penetration, NFI, RFI.

1. Introduction

TBM performance optimization has been the subject of many research studies and field test trials. In this regard, some major TBM cutterhead design characteristics including cut spacing and specific energy are studied in laboratory using linear cutting machine tests, rotary cutting machine tests, and numerical simulations. The summary of the results of these studies show, in order to reach to an optimum excavation, the ratio of cutter spacing to penetration (S/p) shall be varied to reach to a minimum specific energy (SE). At this SE, the rolling force required to generate a unit volume of the excavated rock is comparably lower. One note is that, in practice rolling force is much lower than the normal force, hence it is not a major concern in performance optimization as long as its value fall within its permissible limit defined by the maximum cutterhead torque. In this paper, an extensive database compiled by the author during past 10 years are used to investigate the parameters maximizing the field TBM penetration and advance rate. In this regard, two new formulas are derived from the actual field data of many projects to evaluate cutter normal force and rolling force. These new formulas are used to optimize the cutter penetration considering TBM operational constraints.

2. Methodology

In order to improve the strategies for the evaluation of the normal force and rolling force, an attempt is made to use the information of the database to generate practical formulas for the normal force and rolling force using regression analysis. In order to improve the prediction performance, the objective parameters are normalized with the cutter penetration. With this strategy, the normal force is transformed to a parameter called, normal force index (NFI) (Eq. 1) and the rolling force is transformed to a parameter called, rolling force index (RFI) (Eq. 2).

$$NFI = F_n/p \quad (1)$$

$$RFI = F_r/p \quad (2)$$

where:

NFI is normal force index in kN/mm/rev,

F_n is cutter normal force in kN,

p is cutter penetration in mm,

RFI is rolling force index in kN/mm,

F_r is cutter rolling force in mm.

3. Results and Discussion

Eq. 3 and 4 show the Minitab outputs for the best fitted model for the evaluation of NFI and RFI based on different step forward regression analyses. It should be noted that p-value of less than 0.05 represents high significance of a parameter in a multiple regression analysis. VIF (variance inflation factor) of less than 10 guarantees a low collinearity between dependent parameters.

$$NFI = 0.117 \cdot UCS^{0.5464} LS^{0.75} \left(\frac{S}{76.2}\right)^{1.379} \left(\frac{T}{19}\right)^{1.039} \left(\frac{d}{432}\right)^{1.3} \quad (3)$$

$$RFI = 0.00686 \cdot UCS^{0.3187} LS^{1.063} \left(\frac{S}{76.2}\right)^{1.158} \quad (4)$$

Where:

UCS is uniaxial compressive strength in MPa,

S is cutter spacing in mm,

LS is average linear speed of the cutters in m/min,

T is cutter tip width in mm,

d is cutter diameter in mm.

The cutter force-penetration interaction diagram is constructed on a chart with p on the x axis and F_n on the y axis. In this chart, the upper boundary is defined by the maximum cutter load capacity, the farthest right hand side boundary is determined by the cutter geometry limit, and the upper right hand boundary is defined according to Eq. 3 and 4. As seen in Fig. 1, the extent and location of upper right hand boundary is dependent on the level of RPM used. As the RPM becomes higher, the extent of this boundary becomes larger.

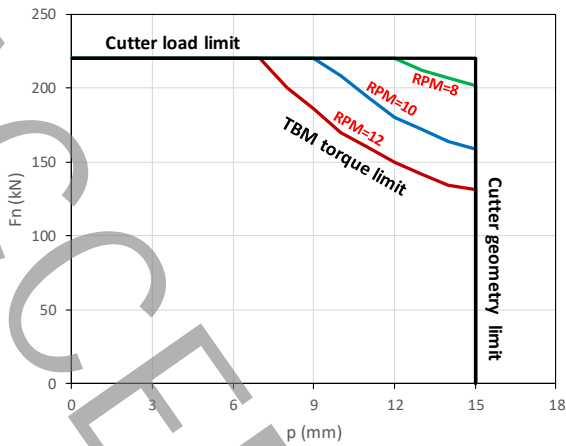


Figure 1. Relationship among normal force, penetration, torque, and RPM

4. Conclusions

This study provides an extensive data analysis for the optimization of hard rock TBMs' performance using

a compiled database of various information of many projects from around the world. In order to enhance the prediction of cutter forces (i.e. normal force and rolling force), two new formulas are developed using the cut and cutter geometry information (i.e. cutter penetration, cutter spacing, cutter diameter, tip width, etc.) and uniaxial compressive strength to evaluate normal force index (NFI) and rolling force index (RFI). An interesting outcome of the analyses conducted for NFI and RFI is that both of these parameters are function of linear speed of the cutters.

On the basis of empirical formulas obtained for NFI and RFI, a procedure is offered to optimize the TBM operation in order to obtain maximum TBM penetration and maximum TBM advance rate considering the effect of RPM and the operational limits for cutter load capacity, rolling force limit, and cutter geometry constrains. The outcomes of this procedure can be used to define optimum RPM, penetration, and intervention interval length, in order to maximize the TBM advance rate and to minimize the TBM downtimes.

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