Science Arena Publications
Specialty Journal of Mining and Geological Engineering
Available online at www.sciarena.com
2018, Vol 1 (1): 23-32

Estimation of the TBM Penetration Rate Using Strain Energy and Drop Modulus Using ROCKLAB Software

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Abstract: *Prediction of tunnel boring machine penetration rate is very important because it is highly related to many parameters such as rock mass quality, rock properties and etc. Penetration rate parameter is an important part of any mechanized drilling project. This coefficient is defined as the drilled interval divided by the machine operating time during a continuous drilling process and is a function of rock parameters, machine specifications, and operator. The accurate estimation of penetration rates for designing time, cost control, and the choice of drilling methods is required. In this paper, an estimate of the TBM penetration rate was made using strain energy and a drop modulus. The case study for this research is the Rabar-Kerman Water Transfer Tunnel Project. The best obtained equation for the final values including the strain energy ratio and the drop modulus is obtained as a logarithmic function.*

$ROP=0.880\ \ln(\Psi/\omega)+10.76$

$R^2=0.73$

The final ROP relationship is based on the amount of penetration in terms of mm / res and Ψ/ω*, which is the ratio of strain energy to drop modulus. Also, according to the results, it is observed that by increasing the ratio* Ψ/ω*, the amount of penetration rate increased initially, and with more increase in the ratio of* Ψ/ω *the values of the penetration rate of the TBM device in the studied project were getting constant. Based on the results, the maximum value of* Ψ/ω *in the Rabar-Kerman Water Transfer Tunnel Project is 11.4 mm/rev.*

Keywords: *Strain Energy, Drop Modulus, The Penetration Rate, TBM*

INTRODUCTION

Mechanized tunneling in Iran is significantly increasing with tunneling machines of all cross sections. Considerations such as geological conditions, the type of TBM machine, specifications and the ability of the machine, are necessary to improve tunneling performance. One of the many important issues affecting the penetration rate (ROP) and the coefficient of productivity of the entire tunnel drilling device is the geological conditions of the mass of the tunnel route. Engineering geometric parameters including orientation, conditions and frequency of joints and fractures in the massif, as well as primer characteristics such as strength and shear, are the determining parameters for the evaluation and analysis of the entire excavation machine in the rock. Along with this information, with the characteristics of the machine, such as propulsion and power, it is possible to estimate the penetration speed of the machine (Alber, 1996).

The application of tunnel bricks in long tunnel drilling as a standard method has been considered in the tunnel industry. Different types of tunnel machines are designed and constructed for different terrain. The choice of suitable tunneling method and the choice of machinery in accordance with the above methods are based on the possibility of estimating the drilling speed of these machines. Obviously, in mechanized drilling, the impact rate of the machine affects the completion time of the project and, consequently, the cost, and plays a major role in the choice of mechanized drilling as a method of drilling. Therefore, predicting the penetration rate is an important part of any mechanized drilling project. The accurate estimation of infiltration rates is essential for planning, controlling costs and choosing a drilling technique. The prediction of TBM performance is one of the most important factors in choosing this machine and aims to estimate the proper amount of power behind the blade and the optimum torque of the machine. Machine specifications including the force applied to each disc, the distance and diameter of the discs, the speed of the disc, the capacity of carrying heavy blocks by the machine, vibration resistance, the diameter and curvature of the drill, the support tools, the amount of cutter's firing and rock mass characteristics (including type, frequency and orientation of joints, porosity, drilling ability, hardness and rock resistance) are two factors affecting TBM performance.

The most significant factors affecting the ROP can be categorized into three classifications: massif properties, machine characteristics, and tunnel geometry (Bruines, 1998). Rock mass properties are characterized by the intact rock as well as the discontinuities of the massif. The most crucial parameter of the intact rock that affects the ROP is uniaxial compressive strength (UCS); the higher the rock strength, the lesser the penetration rate is. The most significant machine technical features that influence the TBM penetration rate are the type and diameter of cutter disk, thrust force of each disk, cutter spacing, as well as operator proficiency. Moreover, tunnelgeometry is a critical parameter influencing penetration rate which affects numerous parameters (e.g. RPM, torque, and total power consumption) (Alvarez, 2000). Principal factors affecting the ROP are shown in Figure 1.

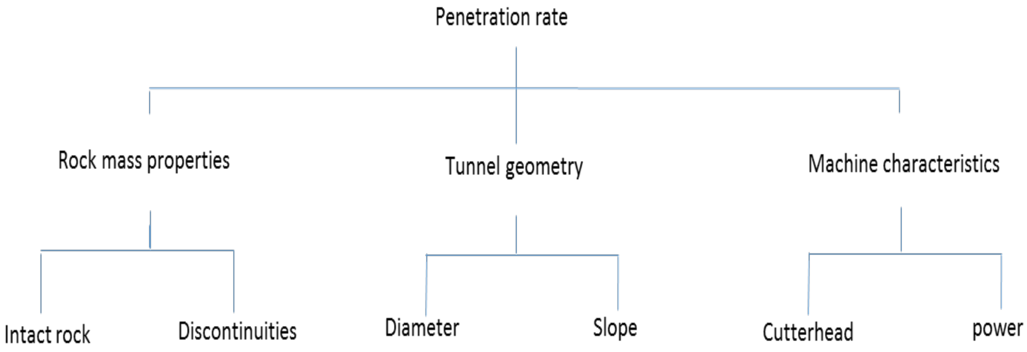

Figure 1: Principal factors affecting the penetration rate

Various experimental analyses (i.e., Brazilian tensile strength (BTS), Taber abrasion, uniaxial compressive strength (UCS), Schmidt hammer, Shore hardness, drilling rate index tests and point load index) has been developed to predict the ROP (Barton, 1999, 2000; Howarth et al. 1986; McFeatSmith 1999; Ozdemir 2007; Pang et al. 1989; Roxborough and Phillips1975; Yagiz 2002; Yagiz and Ozdemir 2011). Additionally, artificial intelligence has been utilized (e.g., Grima et al. 2000; Benardos and Kaliampakos 2004; Yagiz et al. 2009).

Moreover, numerous models are advanced to predict TBM performance such as single factor models (Graham, 1976; Farmer & Glossop, 1980; Nelson, 1983; Hughes, 1986; Rourke, et.all, 1994) or multiple factors models (Rostami, 1997; Bruland, 1998; Nelson, et all. 1999; Cheema 1999; Barton 2000) risk matrix method (Moradi and Farsangi, 2014), and the rock mass classification system (Ribacchi and Fazio, 2005; Sapigni et al., 2002).

In this paper, an estimate of the TBM penetration rate using strain energy and a fall modulus will be considered. A case study of this thesis is a water transfer tunnel project. Various models have been proposed to predict the amount of special drilling energy. All of these models are based on various parameters that can be categorized into three categories: mechanical rock properties, disk dimensions, and cutting geometry. In this research, the concept of crustal rock mass was used to provide empirical relationships to estimate the TBM penetration rate. The strain energy is equal to the surface below the stress-strain diagram and depends on various parameters such as rock mass behavioral model, peak parameters and residual rock mass, peak strain and residual rock mass.

Finally, by performing a statistical analysis on the obtained results, we have presented relationships for estimating the TBM penetration rate based on rock mass energy and drop modulus in a rock mass with different behaviors.

Penetration Parameter

The tunneling drill (TBM) penetration parameter is one of the important parameters that is defined as the length of drilling divided by the operating time during a continuous drilling step. The degree of TBM penetration depends on the characteristics of the device and the properties of the rock mass. When the TBM operates, a stopwatch records the TBM at all operating times. These operating times are used to calculate the penetration rate (ROP) as a measure of the cutting progression at each time period drilling unit. The ROP is often calculated as a typical hourly average based on a certain time criterion (e.g. moment, hour, shift, day, month, year, or even the whole project), and the basis of the calculation must be clearly defined.

Also, the penetration rate can be calculated based on the drilled distance due to the header turning and is cited as momentary penetration. Several methods are used to predict this parameter, such as experimental, experimental and analytical methods. In general, this parameter is predicted based on one or more of the following principal principles: mapping and field experiments, small and large scale laboratory tests.

Input parameters for estimating the strain energy profile include rock properties, pre and post rock deflection properties and rock mass behavior.

Strain Energy Theory

The area under the stress-strain curve is called strain energy. As stated, strain energy is calculated based on rock mass behavior, pre and post-failure properties, and maximum and post-maximum strains.

Hooke-Brown (1997) provided guidelines for estimating the types of post-rock mass failures with respect to rock mass quality. These instructions are based on a variety of stones:

- For a very high solid rock mass and high geological strength index (90> GSI> 70), the behavior of the rock mass is fragile;
- For an average interconnected rock (65> GSI> 50), moderate stress levels cause joint failure, and the stone becomes a cavity and soil.
- For strongly hybrid rock (50> GSI> 40), strain hardening is assumed
- For very weak rock (30> GSI), rock mass has plastic-elastic behavior and no flexibility is assumed;

These concepts are illustrated below. The strain softness behavior can be accompanied by a completely brittle behavior as well as behavioral plastic, resulting in fragile and plastic behaviors being specific cases of strain softness behavior described by Alejano et al. (2009a, b).

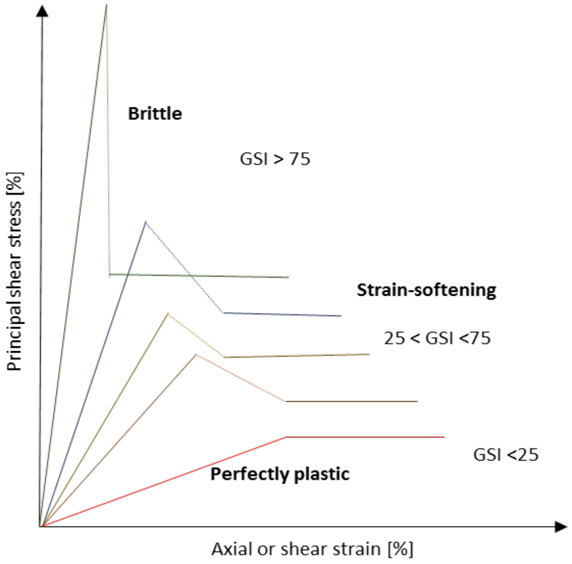

Figure 2. Strain Softening

Drop Module

If the entangled tension is not considered in the calculation, the drop modulus can be estimated according to the following equation (Alejano et al., 2009a):

$$M = \frac{E_{rm}}{0.08GSI - 7} \qquad for\ \ 25 < GSI < 75 \tag{1}$$

A more complicated way to estimate the falloff module, including the effect of $\sigma_{ci}$is as follows:

$$M = \frac{E_{rm}}{0.0812\left(GSI + \frac{\sigma_{ci}}{10}\right) - 7.66} \qquad for\ \ 20 < GSI < 75 \tag{2}$$

The following equation is used as the first approach to estimate the falloff module, if one of the complex strain smoothing models used with the enclosure stress is dependent on the desired drop type (Alejano et al.2009a, b):

$$M = \frac{1000E}{GSI.\sigma_3 + 75GSI - 255\sigma_3 - 5875} \qquad for\ \ 5 < GSI < 75 \tag{3}$$

The most complex equation for estimating the drop modulus is defined as:

$$M = \frac{E_{rm}}{1 - \left[\left[\frac{8.66 - 0.0812(GSI + \sigma_{ci})}{8 - 0.08GSI}\right] . \left[\left(\frac{225 - GSI}{1000}\right) . \sigma_3 + \left(\frac{55 - 0.6GSI}{8}\right)\right]\right]} \tag{4}$$

This equation is for GSI values between 20 and 75.

Estimation of Strain Energy Ratio

According to the subsequent equations, Dehkordi et al. (2011, 2013) proposed a method for estimating the ratio of residual strain energy after failure to stored strain before failure (called strain energy ratio). In this method, strain energy was estimated in both parts before and after failure, with assumption of linear behaviors before and after failure.

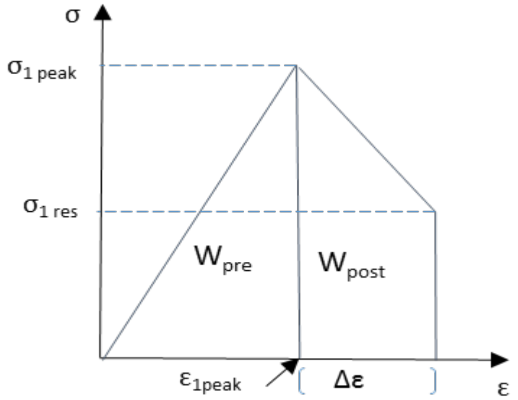

Figure 3. Save energy stored and remaining before and after failure

Then the strain energy (w) is calculated in advance and after failure, based on the following equations:

$$W_{pre} = \frac{1}{2}\sigma_{1_{peak}}.\varepsilon_{1_{peak}} \tag{5}$$

$$W_{post} = \frac{1}{2}\left[\sigma_{1_{peak}} + \sigma_{1_{res}}\right].\Delta\varepsilon \tag{6}$$

In these equations, W_{pre} and W_{post}, respectively, reserve the strain and the remaining residual strain before and after failure; $\varepsilon_{1_{peak}}$ is the amount of strain at the peak and $\Delta\varepsilon$ represents the strain after peak (strain change from maximum to remainder) , Which is estimated according to the following equations:

$$M = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{1_{res}} - \sigma_{1_{peak}}}{\varepsilon_{1_{res}} - \varepsilon_{1_{peak}}} \tag{7}$$

$$\Delta\varepsilon = \frac{\sigma_{1_{res}} - \sigma_{1_{peak}}}{M} \tag{8}$$

In the next step, the strain energy ratio, Ψ is calculated:

$$\Psi = \frac{W_{post}}{W_{pre}} \tag{9}$$

The Steps to Do the Calculations

The following steps have been taken to calculate the following modulus.
The input data for the Rocklab software is as follows:

- Infiltration rate
- σ_{ci}
- Primary GSI (Peak)
- M Hoek-Brown Factor
- D Disturbance Factor
- Specific mass of rock mass
- Tunnel depth
- The remaining GSI based on the proposed relationship (Cai, 2007)

$$GSI_r = GSIe^{-0.134GSI}$$

- Mb and S and Hoek-Brown metrics

- In the following, the values of σ1 and σ3 will be calculated based on the Hoek-Brown criterion (Dehkordi, 2014).

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a$$

Also, values C and φ will also be presented.
Finally, Er is extracted to calculate the drop module from the software.
The following is also used to determine the strain energy:
Based on the information entered into the software in the previous step, the amount of ε_{peak} is initially calculated based on the Sakura and Guelian relationships.

$\log \varepsilon_c = -0.25 \log E - 0.85$ Sakura Relationship
$\varepsilon_{peak} = 1.5\varepsilon_C$ Guelhe's relationship

- The fallout module is also calculated in the previous step.
- Also, σ_1 has already been calculated and the σ_{peak}value is also obtained.
- As a result, the value $\boldsymbol{\varepsilon_{residual}}$ is obtained. Then, the surface under the curve is calculated and the strain energy is obtained. Also, the strain energy ratio is determined based on the two peak and residual sections.

Determine the Final Relationship

In the previous sections, we determined the relationship between the TBM penetration rate based on the strain energy ratio as well as the modulus of decline. Given the purpose of the dissertation, it is necessary to apply a more comprehensive relationship.
Therefore, the $\frac{\Psi}{\omega}$ ratio is used to simultaneously examine the effect of the modulus reduction coefficient and the strain energy ratio on the TBM penetration rate parameter in the water entanglement tunnel project.

Table 1 The values of the final relation

item	Section	Mass rock	Penatration Rate (mm/Rev)	Ψ	ω	Ψ/ω	M Gpa
1	RT1	Gary Andesite	7.4	0.01	3.103	0.003291048	62
		Basalt Lithic	3.8	0.003	11.32	0.000271576	258
		Tuff	9.93	0.028	1.141	0.024247201	11
2	RT2	Basalt	7.6	0.02	2.198	0.009080718	47
		Basaltic	9.86	0.094	0.832	0.112554516	11
3	RT3	Gary Basalt	3.3	0.012	4.862	0.002523997	143
		Andesite Lithic	3.35	0.007	6.375	0.001104183	316
		Tuff	9.95	0.061	0.708	0.08611384	11
4	RT4	Tuff	9.98	0.254	0.196	1.299056625	1
		andesite	9.87	0.121	0.667	0.181718561	10
5	RT5	Basalt	4.2	0.013	3.819	0.003487347	141
6	RT6	Flysch Rock types	8.79	0.129	0.521	0.247108641	3
7	RT7	Tuff	9.97	0.325	0.181	1.797731392	1

The data distribution and penetration rate are shown in the following figure:

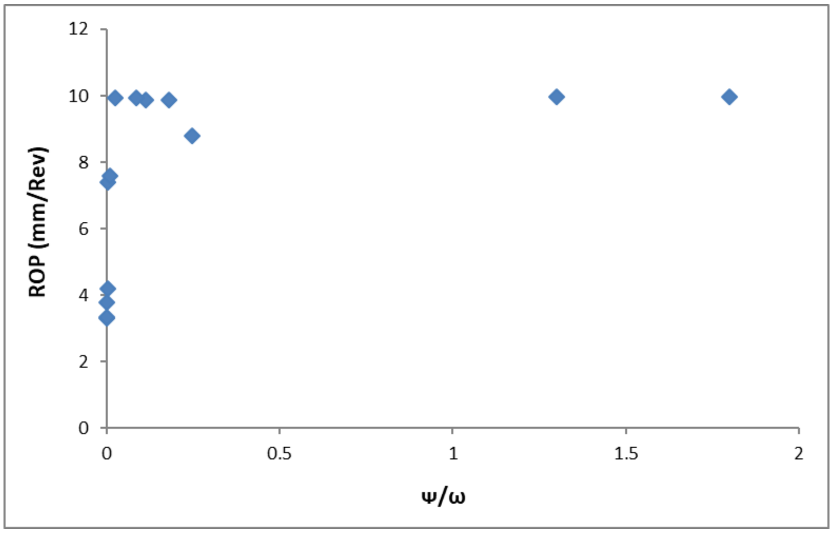

Figure 4: Data Dispersion and Infiltration Rate

Based on the regression analysis, the following regression curves and penetration rates are displayed:

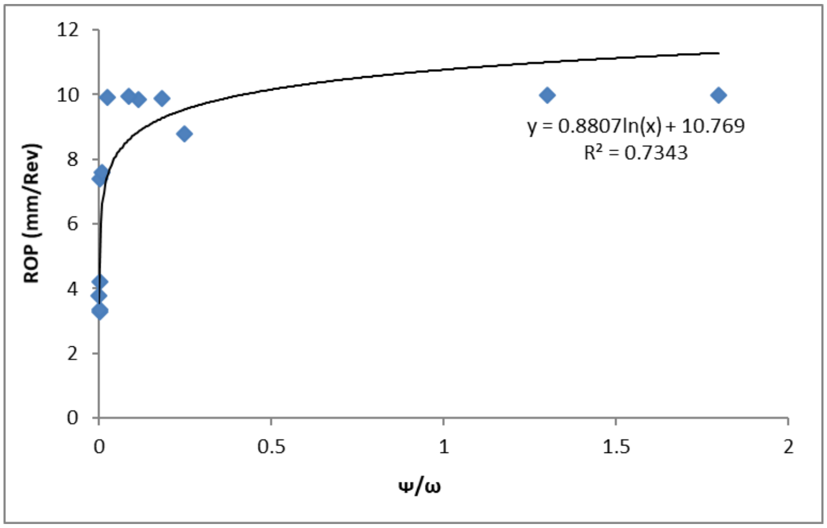

Figure 5: Data regression curve and penetration rate

The best obtained equation for these values is obtained as a natural logarithm function.

$ROP = 0.880 \ln(\Psi/\omega) + 10.76$
$R^2 = 0.73$

In this regard:
ROP: Penetration value in mm / res
Ψ/ω: the ratio of the strain energy to the modulus reduction coefficient

According to the results, it can be seen that by increasing the ratio Ψ/ω, the amount of penetration rate in the studied project increases, and eventually becomes asymptotically, and in the value $\Psi/\omega = 2$ the amount of penetration into the amount Sustainable 11.4 mm / rev.
Therefore, according to the results, the amount of penetration 11.4 mm / rev is the final limit for the water transfer tunnel project.

Conclusion

The most important results and findings of the research are as follows:
Based on the regression curve, the modulus data of the drop and penetration rate have been observed that the governing equation is as follows.
The best obtained equation for these values is obtained as an exponential function.

$ROP = 0.00012M^2 - 0.05930M + 10.14714$
$R^2 = 0.96$

In this regard:
ROP: Penetration value in mm / res
M: The drop module in GPa

Based on the calculations, the regression curve of the strain energy ratio and the infiltration rate data for field and computational values are presented. This relationship is defined as follows:

$ROP = 1.606 \ln \Psi + 12.89$
$R^2 = 0.69$

In this regard:
ROP: Penetration value in mm / res
Ψ: strain energy ratio

The best obtained equation for these values is obtained as a natural logarithm function.

$ROP = 0.880 \ln(\Psi/\omega) + 10.76$
$R^2 = 0.73$

In this regard:
ROP: Penetration value in mm / res
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