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The Time and Cost Prediction of Tunnel Boring Machine in Tunnelling

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Abstract: Making use of microsoft visual studio. net platform, the assistant decision-making system of tunnel boring machine in tunnelling has been built to predict the time and cost. Computation methods of the performance parameters have been discussed. New time and cost prediction models have been depicted. The multivariate linear regression has been used to make the parameters more precise, which are the key factor to affect the prediction near to the reality.

Key words: tunnel boring machine; time prediction; cost prediction; assistant decision-making; multivariate linear regression

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0 Introduction

The time and cost prediction, which are getting on slowly, are always the key factor that determine whether the assistant decision-making system is utility. So it is necessary to research on the time and cost needed in a special project and their probability distributing, which could be used as a credible basis for signing a contract and as a tool to optimize construction plan and to reduce cost. System of Okubo[1] has three phases: ① Check the environment so that it is suitable for the fundamental requirements in which tunnel boring machine (TBM) is used; ② Estimate the performance of the TBM in terms of thrust force, rolling force, penetration rate, rotational speed, advanced rate and etc.; ③ Evaluate the values estimated in the second stage in reference to the various models. There are lots of time and cost prediction models and rules in the third stage. The database system[2], which was established based on the collected history events, was discussed in the dissertation of Chistopher Laughton, where the parameters described in the database system and their relationship between each other have been depicted particularly. Al Jalil had discussed the way to make prediction more precise with the probability density function of parameters, the way to create the probability density function[3]. And the theory of mechanics of cutter has been depicted in Ref. [4]. But a lot of new type of cutters and new technologies has been used in TBM, so the old prediction methods must be modified or rebuilt. So a new prediction model has been depicted and the time and cost prediction models which have been built based on the research of internal and overseas have been depicted. In order to make the parameters more precise, the multivariate linear regression has been used.

1 Performance Parameters of TBM

1.1 Penetration Rate

The penetration rate can be calculated by V_P and L_P:

$$V_P = L/t_b \tag{1}$$

$$L_P = 1\,000V_P/(n \times 60) \tag{2}$$

where, V_P is the average penetration rate at which the cutterhead bores rock per hour, expressed in m/h; t_b is the time of operation of cutterhead, expressed in h; L is the distance should be mined, expressed in m; L_P is the penetration per revolution of cutterhead, expressed in mm; n is the rate of cutterhead rotation, expressed in $r \cdot m^{-1}$;

1.2 Utilization

Utilization is defined as the percentage of time in boring t_b per unit shift time T.

$$U = 100 \times (t_b/T) \tag{3}$$

1.3 Advance Rate

A shift time includes the boring time t_b and non-boring time t_n. And the non-boring time is constitutive of regrip time and time wasted by other delays. So the advance rate η is defined as the distance mined in a given amount of shift time. Substituting Eqs. (1) and (3) into Eq. (4) and Eq. (5), they will be got

$$\eta = L/T \tag{4}$$

$$\eta = (V_P \times U)/100 \tag{5}$$

2 The Prediction Model and Analysis

2.1 The Prediction of Penetration Rate

There are lots of factors that affect the penetration rate, such as intact rock strengths, weather, crack density, rock mass conditions, rock texture and etc. Now there are lots of different prediction models depicted by the researchers of the whole world. For example, the prediction of penetration rate given by Tarkoy[5], as Eq. (6) and (7), the equations of penetration rate, as Eq. (8) and (9), given by Sundin and Wanstedt in 1994[6].

$$V_P = 3.716 - 0.019H_T \tag{6}$$

$$H_T = H_R\sqrt{H_A} \tag{7}$$

The above equations are applicable to such rock types: dolomitic limestone, shale and siltstone, sandstone, quartzite and schist. And the equations must fulfill the range of variables as follows:

$$0.076 \leqslant V_P \leqslant 3.716$$

$$2 \leqslant H_T \leqslant 242$$

where, H_T means total hardness; H_R means Schmidt (L-type) hammer rebound and H_A means rock abrasion hardness.

$$I_B = P_B K_J \tag{8}$$

$$V_P = 0.06 I_B F_n n \tag{9}$$

where, I_B means drilling ability index; P_B means penetration index; K_J means factor for weakness planes present in rock mass; F_n means thrust force per disc cutter, expressed in kN.

The above equations are applicable to such rock types: mica schist, granite and gneiss. And the uniaxial compressive strength range is 65-220 MPa, the point load range is 1-9, the fracture toughness range is 2.2-3.3 $MN \cdot m^{-3/2}$.

2.2 The Prediction of Utilization

The method of utilization prediction given by Earth Mechanics Institute at the Colorado School of Mines takes into account as follows[7]: the gradient of tunnel, method of muck, water inflow, the radius of curvature of horizontal curve and rock mass environments, etc. The approach is summarized in Table 1. All the times in model have been expressed in h.

2.3 The Time and Cost Prediction Model

Each subsystem can be treated as a class during the modeling according to the principle of Object Oriented Programming (OOP) language, which is called entity class. And each object driven from entity class has at least three attributes, defined as follows:

① Capacity of equipments: For example, the rate of cutterhead rotation and volume of muck that can be transported out of the tunnel per hour.

② Reliability of equipments: There is a function that defines the probability at given time the equipment working.

③ Degree of the equipment has been used: The delays should be multiplied by a right coefficient according to the degree of equipment has been used.

Each activity can be treated as a class, which was called activity class. And each object driven from activity class has at least two attributes, defined as follows:

① Time of activity: The time includes the best time, the worst time, the average time and the resources needed to finish the activity. And the resources include material, equipment, labor, power and etc.

② Priority and connectivity of activity: This attrib-

Table 1 Prediction of utilization of TBM using the Colorado school of mines method

Equations	Definition of terms
$U=\frac{t_b}{t_b+t_m+t_a+t_r}\times 100$	t_m: Time of machine delays;
$t_m=t_1+t_2$	t_1: Scheduled maintenance;
$t_1=0.067\times t_b$	t_2: Unscheduled maintenance;
$t_2=f_4\times t_b$	t_r: Regrip time;
$t_r=f_3\times L$	t_a: all system delays;
t_a take into account to such parameters as follows:	t_s: Surveying delays;
$t_s=(\frac{68\ 711}{R^2}+0.003\ 3)\times L$	t_w: Water inflow delays;
$t_w=f_6\times L$	t_u: Utilities delays;
$t_u=(\frac{0.029\ 5}{0.001\ 13\times\theta})\times L$	t_p: Support installation;
$t_p=f_9\times L$	R: Radius of curvature of horizontal curve;
	L: Length of tunnel;
	$f_4=\begin{cases}1.0, \text{ start-up}\\ 0.324, \text{ production-phase}\end{cases}$
	$f_6=f(\mu,\theta)$
	μ: Water inflow rate;
	θ: Slope of tunnel;
	f_9: Function of ground class.

ute is the key factor that affects the route of the network graph.

The iterative way to estimate utilization has been depicted, which was based on two equations defined as follows:

$$U=\frac{100}{1+\sum_{i=1}^{N}\frac{T_i}{T_i'}} \tag{10}$$

where, U is average utilization of TBM in tunneling; T_i is mean time of the ith repair or delay (Unit: h); T_i' is mean time between two instance of the ith failures (delays) in tunnelling; N is number of categories of delays.

In Eq. (10), a dummy failure has been introduced. We should consider that the time between the last repair and the finish of the revolution is equal to the mean time between two instance of the ith failures (delays) in tunnelling.

The second method to estimate utilization has been depicted as the following:

$$U=\frac{100}{1+\sum_{i=1}^{N}\frac{T_i}{T_i'}-\frac{1}{T}\sum_{i=1}^{N}T_i} \tag{11}$$

In Eq. (11), some hypothesis conditions must be fulfilled. Firstly, in every shift or during the whole working period, the each mean time of the ith repair or delay should be changed lightly in the same condition. And there are about 10 h in each shift. Secondly, the value of t_b, which is the time of operation of cutterhead, changes lightly in the same rock mass condition. Thirdly, the number of categories of delays changes lightly in the same rock mass condition. Finally, the time between the last repair and the finish of the revolution is equal to the mean time between two instance of the ith failures (delays) in tunneling.

In the cost prediction model, some parameters must be considered, such as:

① Cutter wear cost per mined distance;

② Cost associated with power on a shift time;

③ Cost associated with labor on a shift time;

④ Cost associated with rock support based on the cumulative length mined in each behavior-classfied cell.

So as to make sure that the prediction results calculated by this model are near to the reality, the value of the penetration rate, T_i and T_i' must be calculated precisely. How to calculate precisely the value of each parameter is always the key factor that determines whether the assistant decision-making system is utility. And those values will change with the variety of rock mass conditions, the distributing of tunnel, the type of TBM and etc. Moreover some parameters' values can be calculated with an equation, but some can not be calculated precisely, which must be calculated by the method of multivariate linear regression. With this method, we can get the probability density function of those parameters and then can get a precise value.

For example, Eq. (12) can be used when we are calculating regrip time.

$$t_r=(\frac{4\ 400}{R^2}+0.029\ 8)\times L \tag{12}$$

The method of multivariate linear regression must be used when we are calculating the value of unscheduled maintenance (t_2) or water inflow delays (t_w).

For example, the water inflow delays (t_w) can be calculated as followed. The model is defined by the linear Eq. (13). Only the method has been depicted and the difference of the precise between models had been depicted in Refs. [8,9].

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + e_i \quad (i = 1,2,\cdots,n) \tag{13}$$

in Eq. (13), the subscript i means the ith sample.

The multivariate linear regression equation expressed in matrix as follows:

$$\boldsymbol{Y} = \boldsymbol{X}\hat{\boldsymbol{\beta}} + \boldsymbol{e} \tag{14}$$

In Eq. (14), the $\hat{\boldsymbol{\beta}}$ is the row vector with k elements which is constitute of the least multiply of the regression coefficient. And e is defined as the departure of the statistic.

Where, y, x_1, x_2 and x_3 are elements of matrix, And y is the water inflow delays; x_1 is the quantity of water inflow; x_2 is the grade of tunnel; x_3 is the classification of rock mass; $\boldsymbol{e}$ is the departure of the statistic.

3 Conclusion

The time and cost predictions could be used as a credible basis for signing a contract and as a tool to optimize construction plan and to reduce cost. The prediction models of the assistant decision-making system must be modified because that technology of TBM is improving on, the capability of TBM is better. And the precision of the prediction can be improved by the method of multivariate linear regression.

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