An introduction to RAM analysis of EPB tunnel boring machine

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A B S T R A C T

Earth pressure balance tunnel boring machines (EPB - TBMs) are favorably used in construction of tunnels in urban areas. These more expensive machines with high operational costs require an exclusive study and knowledge on these machine components and subsystems and their failure and downtimes for time planning, cost control and performance prediction with a high accuracy. For achieving these aims, guidelines for reliability, availability and maintainability (RAM) analysis of an EPB machine are completely expressed in present study. Gathering and recording all daily failure and repair times and other maintenance tasks, dividing the machine into subsystems (including mechanical subsystem, electrical subsystem, hydraulic subsystem, pneumatic subsystem and water subsystem), graphical tests (trend test and correlation test), statistical tests and analysis are discussed in detail. Therefore, RAM analysis can be applied for EPB-TBMs in all mechanized tunneling projects and it is suggested to the tunneling communities and companies to fix these instructions in their programs.

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1. Introduction

Tunnel boring machines (TBMs) are being used more and more in construction of tunnels in approximately all type rock masses and geological conditions, especially in tunnels with the length of more than 2 km (Kolymbas, 2005). Nowadays, the commonly used mechanized method in modern urban tunneling construction is earth pressure balance (EPB) tunneling. In his method, the face of tunnel is supported by mud, formed of the mined soil. The popularity of EPB tunneling is due to its high advance rate, minimal ground structures disturbance and etc. The mined tunnel is supported by installing segmented lining from the rear part of the shield TBM after the excavation. The risk of settlement and subsequent destruction to ground structures is high. As a result of development of EPB machines, such risks have been reduced. Designing the tunnel boring machines, powerful and multimillion dollar machines is one of the most important technologies and their performance is directly related to their uptime and the system’s reliability, which directly concludes operational life cycle and efficiency of excavation.

A reliable evaluation of excavation rates is necessary for time planning and cost control in order to make TBMs economic in comparison with the conventional drill and blasting tunneling (Sapigni, et al. 2002). Previously studies have been done on TBM performance (advance rate, penetration rate and utilization factor) by considering rock mass classifications and geological conditions (Barton, 1999; Sapigni et al. 2002; Yagiz, 2002, 2007 and 2011; Hassanpour et al. 2009, 2010 and 2011; Hamidi et al. 2010). Frough et al. (2012) studied on TBM utilization using rock mass rating system using a database of 682 days of operation and presented the relationship between utilization factor, geological and rock mass related downtimes, while the geological and rock mass related downtimes were about 20% of the operation times and the machine related downtimes were about 60%. Moreover, Laughton (1998) investigated the downtime and delays of 10 mechanized tunneling and indicated that more than 60% of total delays are associated with TBM system delays. Therefore machine failures and downtimes are necessary to be considered for assessment and improvement of TBMs availability and utilization factor. It is notable to say that the utilization factor is reported from 5 to 50% or less in different projects (Barla and Pelizza, 2000).

Failures and downtimes of mining and tunneling equipment may lead to serious additional costs to project. Reliability, Maintainability and Availability (RAM) analysis and risk management is therefore, essential in these projects (Jafari et al. 2009). According to various civilian and military studies, it is possible to reduce preventive and corrective maintenance task times by 40% to 70% with planned maintainability design efforts (Dhillion, 2008). The literature of researches on RAM analysis of mining equipment refers to end of 1960’s (Hoseinie, 2011). The Basic and practical studies on reliability analysis of mining equipment were presented by Kumar and Granholm (Kumar and Granholm, 1988). Kumar (1990) analyzed the reliability of loud haul dumper (LHD) by dividing of this machine (system) into 4 series subsystems including engine, hydraulics, brake and transmission subsystems. By studying on regarded LHDs failures and downtimes data, the reliability for each subsystems and finally for LHD is calculated. Further researches about RAM analysis of mining equipment can be seen in ref. (Barabady and Kumar, 2007; Hall and Daneshmend, 2003a and 2003b; Stanek and Venkata, 1988; Samanta et al. 2001 and 2004; Wijaya et al. 2011, Hoseinie et al. 2012, Hoseinie et al.2013).

2. Reliability, maintainability and availability analysis

Reliability, Availability and Maintainability (RAM) is defined as the characteristic of a system and acts as a performance indicator for system quality and performance.

2.1. Reliability

The reliability of a system is defined as the probability that the system will perform its required function throughout a specified time interval when operated under given conditions (Dhillion, 2008). Reliability analysis usually comprises two comprehensive qualitative and quantitative categories. Qualitatively, reliability is defined as the ability of the system to remain functional. Failure Modes and Effects Analysis (FMEA), frequently used in reliability engineering, is a qualitative method and consists of the systematic analysis of failure modes, their causes, effects, and criticality. Quantitatively, reliability specifies the probability that no operational interruptions will occur during a specified time interval (Birolini, 2007). Basically, the quantity of reliability can be achieved by Eq. (1),
\[ R(t) = 1 - \int_{0}^{t} f(t) \, dt \] (1)

Where, \( R(t) \) is the reliability at time \( t \) and \( f(t) \) represents the failure probability density function.

### 2.2. Maintainability

Maintainability is the probability that the system (item) can be repaired and returned to an operational state in a stated time interval, when the repair action is performed in accordance with prescribed procedures. From a qualitative point of view, maintainability is defined as the ability of the system to be retained in or restored to a specified state (Birolini, 2007). Quantitatively, the probability of repair in a given time can be defined by Eq. (2),

\[ M(t) = \int_{0}^{t} f_r(t) \, dt \] (2)

Where, \( M(t) \) is the maintainability function at time \( t \) and \( f_r(t) \) is the repair time probability density function.

### 2.3. Availability

The other important area in RAM analysis is availability analysis. Availability is the probability that a system or item can perform its required function at a given point in time or over a stated period of time when operated and maintained in a prescribed manner (Ebeling, 2010). A system (machine) can be in one of two states, namely ‘up (on)’ and ‘down (off)’. By ‘up’ it is meant that the system is still functioning and by ‘down’ it is meant that the system is not functioning (in fact the system is being repaired or replaced, depending on whether it is repairable or not). Therefore, the state of the system has a binary position,

\[ X(t) = \begin{cases} 
1, & \text{if the system is working at time } t \\
0, & \text{otherwise} 
\end{cases} \]

Where, function \( X(t) \) denotes the status of a repairable system at time \( t \). The instant availability at time \( t \) (or point availability) is defined by,

\[ A(t) = P(X(t) = 1) \] (3)

This is the probability that the system is working at time \( t \). Because finding an explicit expression for \( A(t) \) is difficult, other measures of availability such as steady-state availability of a system have been recommended, which is defined by following equation,

\[ A = \lim_{t \to \infty} A(t) = \frac{MTBF}{MTBF + MTTR} \] (4)

Where, MTBF is the mean time between failures and MTTR is the mean time to repair (Birolini, 2007).

As can be seen in mentioned equations, two time-based parameters TBF and TTR are the base of RAM analysis. \( f(t) \) and \( f_r(t) \) are calculated by determining TBF and TTR, respectively. These parameters can be calculated between to stops of the machine, so considering all of the machine failures and stops in a time interval (for example one operational year); TBF, TTR, MTBF and MTTR could be attained for each subsystem (see Fig.1)

![Fig. 1. TBF and TTR between to stops of machine.](image)

### 3. A review of earth pressure tunnel boring machine
EPB machines are commonly utilized in formations with different and frequently varying ground conditions or in vastly weathered rocks. In fact, an EPB machine is a huge factory of tunneling construction (Merritt and Mair, 2006; Peila et al. 2009). Fig. 2 shows a simplified section of an EPB machine. During the excavation process, rotating cutter head excavates the soil which passes into the pressurized bulk chamber, the machine is then pushed forward by jacks on the thrust system which supplies pressure on the segments (EFRANCE, 2000).

![Fig. 2. Schematic view of EPB machine (EFRANCE, 2000).](image)


Fig. 2 shows only the front part of an EPB-TBM. This huge machine has a backup system which its length may reach 250 m (Herrenknecht, 2002). In order to have a compressive study on performance and RAM analysis of this machine, it is necessary to divide the machine (system) into distinct subsystems, then downtimes and failures for each subsystem should be studied separately and finally the situation of whole system can be derived. In order to have a quick view of an EBP machine, the schematic view of an EPB-TBM designed and manufactured by NFM technologies for line 1 of metro project in Tabriz, Iran, is shown in Fig.3.

![Fig. 3. Schematic representation of a NFM-EPB machine (NFM Technologies, 2007).](image)

As shown in Fig. 3, this machine is composed of Front part and 9 gantries. The front part mainly includes cutter head, working chamber, screw conveyor, thrust arms, front and rear shields, drive unit, air locks and erector. The connecting beams 1 and 2 in front part is a structure that ensures the connection between the front part and the backup train which also include equipment such as skid for foam production, bentonite pressure vessel, dewatering pump, belt conveyor, electric supply cabinet, ventilation duct, control cabin and segment conveyor. 9 gantries, G1 to G9, so called back up system, serve as room for many supporting equipment. This equipment include grouting tank, grouting pumps, air and water distortion, dewatering tank, belt conveyor, industrial air compressor, water pumps units, bentonite mixer, bentonite tank, emergency generator, air ventilator, cool and hot water tanks, etc. The backup system roll on rails fixed on transverse beam placed on the lining and in addition to the accommodation the above equipment, is intended to give way to the service train up to the connecting beam, allow the personnel to circulate (NFM Technologies, 2007).
Currently NFM-EBP machines are favorably used in construction of metro lines in Iran for example, Tabriz metro (2 machines), Mashhad metro (1 machine), Ahvaz metro (2 machines) and Shiraz metro (2 machines). Consequently, RAM analysis of this type of tunnel boring machines is necessary for Iranian tunneling community and companies.

4. RAM analysis of EPB tunnel boring machine

The basic and practical technique for reliability analysis of mining equipment was introduced by Kumar and Granholm. These researchers used a graphical and statistical method for reliability analysis. This method is developed for maintainability and availability analysis. Although this method has favorably been used in RAM analysis of mining equipment, it has not been applied in RAM analysis of EPB-TBMs yet. The present paper suggests this method can be a robust technique for RAM analysis of EPB-TBMs.

RAM analysis, derived from reliable tunnel boring machine operation data, will help specify cost effective maintenance intervals, thereby lessening corrective maintenance actions and downtimes and increasing TBMs reliability and availability. So, it is essential that the required operating data of TBMs, such as all daily times of failures, downtimes and repair times of each component, be accurately recorded by mechanical, electrical and maintenance supervisors. Consequently, the first step in RAM analysis of an EBP – TBM is gathering a suitable database. The second important step is identifying the subsystems of the EPB machine. Since these machines are composed of vast components, it is necessary that these subsystems (and their components) identification be carried out by a group of electrical and mechanical engineers in cooperated to mining and civil engineers. In general, these subsystems could be divided into mechanical subsystem, electrical subsystem, hydraulic subsystem, pneumatic subsystem, water subsystem, etc.

In the third step, the related data (failure and repair times) of each subsystem can be classified for determining the basic parameters of RAM analysis, TBF and TTR. In the next step, by using these calculated values, the graphical and statistical process of RAM analysis for EPB – TBM can be performed. According to previous studies on mining equipment, RAM analysis of EPB machine can be done on the basis of a renewal process, non-homogenous Poisson Process (NHPP) or Branching Poisson Process (BPP). If the TBF or TTR data have a trend, the renewal process should be used; otherwise, non-homogenous poison process or power low process, a time-dependent model, is applied (Samanta, 2001a, 2001b, 2002 and 2004).

The common graphical methods for the trend test include plotting the cumulative failure or repair number versus the cumulative TBF or TTR. An approximately straight line depicts no trend in data (Barabady and Kumar, 2008).

In renewal process the correlation test determines the RAM analysis method. Once data show a correlation, the branching poison process can be utilized. Else, failure or repair data are independent and identically distributed (iid) and can be considered for modeling by a suitable probability distribution function (e.g. Weibull, Exponential, Normal, Lognormal, Gamma, etc.). Also a graphical test for existence of serial correlation is plotting the ith TBF or TTR against i-1th TBF or TTR. If the plotted points are randomly scattered without any pattern, it can be interpreted that the TBF or TTR have no serial correlation (Hoseinie, 2011). Data analysis and determine the best distribution can be done by software packages such as Easy fit, Best fit or Weibull ++. Moreover, the process of distribution fitting and verifying the goodness of fit by these software packages is cited in ref. (Hall and Daneshmend, 2003).

Therefore, using the mentioned equations and software packages, reliability, maintainability and availability for each subsystems of the EPB – TBM can be calculated. Consequently the RAM of whole system (EPB machine) in a series configuration (Fig.4) is achieved by following equations.

![Fig. 4. The main out looked subsystems of EPB-TBM.](image)
\[ R_{\text{series}} = \prod_{i=1}^{5} R_i \]  \hspace{1cm} (5)

Where, \( R_{\text{series}} \) is the series system or configuration reliability, and \( R_i \) is the unit i reliability (Dhillion, 2008).

\[ A_{\text{series}} = \prod_{i=1}^{5} A_i = \prod_{i=1}^{5} \frac{MTBF_i}{MTBF_i + MTTR_i} \]  \hspace{1cm} (6)

Where, \( A_{\text{series}} \) is the series system or configuration availability, and \( A_i \) is the unit i availability (Pham, 2003).

Similarly, maintainability can be calculated as reliability and availability. The process of RAM analysis for EBPTBM is represented in Fig.5.

RAM analysis of this widely used and costly machine can reveal a new point of view in mechanized tunneling field. Furthermore, the performance of these machines can be studied by researchers in order to predict and improve the real availability and utility factor and consequently minimize the machine downtimes and operational costs. Attaining these important goals depend on the exactly recording of each daily maintenance tasks, specially the occurred failure and repair times.

**Fig. 5.** Proposed RAM analysis process of EPB – TBM (Adapted from Hoseinie (2011)).
5. Conclusion

Reliability, availability and maintainability (RAM) analysis of various mining equipment has been done previously, but no general study on tunnel boring machines has been reported yet. In this paper, considering favorable application of mechanized tunneling, utilization of RAM analysis for earth pressure balance tunnel boring machines (EPB – TBMs) is introduced. For this aim, it is suggested that all daily downtimes of machine (TBM-system related downtimes) including failure and repair times and all maintenance tasks exactly be recorded by maintenance supervisors in each project. RAM analysis, derived from reliable machine operation data, could help specify cost effective maintenance intervals, thereby lessening corrective maintenance actions and downtimes, thereby increasing TBMs reliability, availability and utility factor in the early stages of each project. So, it could be applicable to predict the machine performance for the rest of that project or other projects which apply similar machines with a high accuracy. Guidelines for RAM analysis of an EPB machine are expressed in detail and it is suggested to the tunneling communities and companies to fix these instructions in their programs.

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