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RAM Analysis of Hydraulic System of Earth Pressure Balance Tunnel Boring Machine

H. Amini Khoshalan[1*], S. R. Torabi[1] and D. Maleki[2]

[1]Department of Mining, Petroleum and Geophysics, University of Shahrood, Shahrood, Iran;
h.amini@shahroodut.ac.ir, rtorabi@modares.ac.ir
[2]Tabriz Metro Project, Tabriz, Iran; d.maleki@yahoo.com

Abstract

Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) are more popular in urban mechanized tunneling nowadays. For improving the performance of these machines, time planning, maintenance scheduling and cost control in mechanized tunneling, tunnel boring machines should be reliable and maintained effectively and efficiently. For this aim, this paper seeks to study the reliability, availability and maintainability of hydraulic system of EBP-TBM in Tabriz metro in Iran. The failure and repair data were collected during about 26 months of machine operation. Performing trend and serial correlation tests showed that the data are Independent and Identically Distributed (IID) and therefore the statistical techniques were used for modeling. The data analysis showed that the Time Between Failures (TBFs) and Time To Repairs (TTRs) data confirm the generalized Gamma and Gamma distribution respectively. Reliability model indicated that reliability-based preventive maintenance time intervals for 90%, 80%, 70% and 50% reliability level are respectively 2.72, 7.17, 13.1 and 30.16 h. Calculations showed that TTR of this system varies in range 0.17- 6.5 h with 1.54 h as mean time to repair (MTTR). There is an 80% chance that the hydraulic system of EPB-TBM in Tabriz metro tunnel will be repaired within 2.45 h. Also the availability of hydraulic system of this machine is equal to 97%. The result provides a practical foundation and support for the RAM analysis of tunnel boring machines in mechanized tunneling.

Keywords: Availability, Hydraulic System, Maintainability, Reliability, Tunnel Boring Machine

1. Introduction

Tunnel Boring Machines (TBMs) are favorably used in construction of tunnels nowadays. Among various types of TMBs, earth pressure balance (EPB) tunnel boring machines have the most suitability in infrastructure projects such as subways, sewers, water supply, etc. The popularity of EPB-TBMs is due to their fast working speed, high automation level, minimal damage to ground structures and environmental friendliness. Also an EPB-TBM is able to excavate in mixed ground face with soft and hard rock foundation[1, 2]. Tóth et al.[3] presented the case studies of TBM tunneling performance in rock–soil interface mixed ground. Jain et al.[4] studied the performance characteristics of tunnel boring machine in basalt and pyroclastic rocks of Deccan traps in a water supply tunnel in India. Further studies on TBMs performance can be seen in[5-8]. These studies have been performed by considering of rock or soil geological and mechanical characteristics through empirical approach or physically based theories. Nonetheless, there are few documents in the literature regarding the prediction of TBM utilization factor. In a great effort, Frough et al.[9] estimated TBM utilization factor using rock mass rating system and 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%. Also, Frough and Torabi[10] applied the Rock Engineering

**Author for correspondence*

System (RES) for calculating geology and rock mass related downtimes index based on predominant rock mass properties and rock mass related downtimes.

Lack of consideration of the TBM related failures and down times and key parameters for achieving machine's real availability and utilization factor, are the main shortcoming of all reported investigations.Laughton[11] investigated the downtime and delays of 10 mechanized tunneling and indicated that more than 60% of total delays are associated with TBM system delays. Having no general study in literature on tunnel boring machine system related delays, it seems that a comprehensive study on failures and downtimes of TBM system is necessary in order to evaluate machine's accurate availability and utility. Furthermore, failures and downtimes of TBM may lead to serious additional costs to project. Reliability, Maintainability and Availability (RAM) analysis is therefore, essential in a mechanized tunneling project. 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[12].As a first attempt in this filed, guidelines for RAM analysis of EPB-TBMs have been represented by Amini Khoshalan et al[13]. These guidelines are based on the previous studies on RAM analysis of mining equipment, which the basic and practical methods for reliability analysis of mining equipment were introduced by Kumar and Granholm[14].

In this study, EPB-TBM in construction of Tabriz metro tunnel in Iran, manufactured by NFM technology, is divided into five distinct subsystems including mechanical subsystem, electrical subsystem, hydraulic subsystem, pneumatic subsystem and water subsystem. Then filed data of about two years of operation including time between failures (TBFs) and time to repairs (TTRs) of hydraulic subsystem is prepared. Finally, RAM analysis of hydraulic subsystem is performed and reliability, availability and maintainability of hydraulic subsystem are calculated. The result provides a practical foundation and support for the RAM analysis of tunnel boring machines in mechanized tunneling projects.

2. Reliability, Availability and Maintainability Concept

Reliability, Availability and Maintainability (RAM) is a characteristic of a system's long term operation and is a significant approach for reducing maintenance costs and improving operation 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[12,15,16]. 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[17]. Quantitatively, reliability specifies the probability that no operational interruptions will occur during a specified time interval[18]. Basically, the quantity of reliability can be achieved by Equation (1):

$$R(t) = 1 - \int_0^t f(t)\,dt \tag{1}$$

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[18].Quantitatively, the probability of repair in a given time can be defined by Equation (2):

$$M(t) = 1 - \int_0^t f_r(t)\,dt \tag{2}$$

Where, $M(t)$ is the maintainability function at time t and f_r 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[19]. 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:

$$A(t)=P\big(X(t)=1\big) \tag{3}$$

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:

$$A=Limit_{t\to\infty}A(t)=\frac{MTBF}{MTBF+MTTR}=\frac{\text{Up time}}{\text{Up time}+\text{Down time}} \tag{4}$$

Where, $MTBF$ is the mean time between failures and $MTTR$ is the mean time to repair[18].

As can be seen in mentioned equations, two time-based parameters, TBFs and TTR s 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 Figure 1).

3. Case study

Tabriz city with about two million inhabitants is located in northwest of Iran. Due to population growth in this city and traffic problems, preliminary studies for subway system performed in 2002. So a railway network consisting of four lines, with overall length of 60 km and 160 stations is considered. The Length of each twin tunnel of line 1 is 8070 m with inner diameter of 6.88 meters (i.e. diameter of TBMs) that after the installation of segments will be equal to 6 meters[20]. Earth pressure balance (EPB) method is considered as the best method for construction of these tunnels and two EPB tunnel boring machines were designed by NFM technology for this task. A schematic view of main parts of this machine in line 1 of Tabriz metro is shown in Figure 2.

The face is excavated by a rotating cutter head which is fitted with appropriate cutting tools. The resulting material enters the working chamber where a paste like mixture of earth is produced. The pressure in the chamber is controlled and maintained by the combination of the thrust of the EPB which is generated by the thrust cylinders and is transferred to the chamber via the bulkhead and the spoil removal rate which is controlled by the rotation speed of the screw conveyor and the advance of the machine. The final lining of the tunnel is constructed under the protection of the shield and consists of precast concrete segments which interlock creating a solid concrete ring. These are fitted in place by an erector.

In addition to these components, this machine is also composed of the front part connecting beams 1&2 structures that ensures the connection between the front shield and the backup train, including a skid for foam production, bentonite pressure vessel, dewatering pump, belt conveyor, electric supply cabinet, ventilation duct, control cabin, segment conveyor, etc.) and 9 gantries (G1 to G9 with a total length of 92.1m, without the shield) which is schematically showed in Figure 3. The gantries (which house and support equipment including hydraulic pumps, hydraulic motors, hydraulic tank, oil filtrations, including

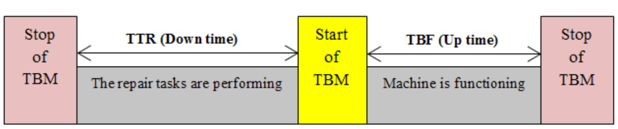

Figure 1. TBF and TTR between to stops of machine.

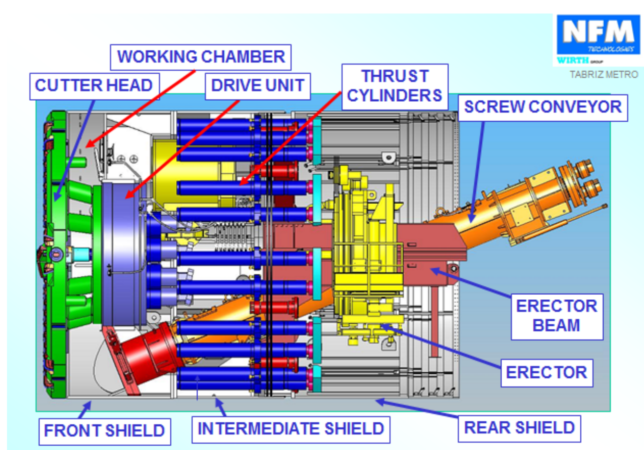

Figure 2. Schematic view of the main parts of Tabriz metro tunnel boring machine[21].

grouting tank, grouting pumps, air and water distortion, dewatering tank, belt conveyor, industrial air compressor, water pumps units, bentonite mixer, bentonite tank, loudspeaker, emergency generator, air ventilator, cooling and hot water tanks, etc.) roll on rails fixed on transverse beam placed on the lining and give way to the service train up to the connecting beam, allow the personnel to circulate, etc.[21]

EPB-TBMs, as a factory of tunneling, could be divided into five subsystems including mechanical, electrical, hydraulic, pneumatic and water subsystem in series configuration as is presented in Figure 4[13].

Hydraulic and electrical subsystems are two major power supplies of EPB-TBMs. These two parts have the key role of power production and its transition to other working parts of the machine. The hydraulic powerhouse supplies hydraulic energy to the various components of the tunneling machine and the high reliability of this part leads to the high machine reliability and successful operation. Since the hydraulic subsystem of the EPB-TBM is quite complex, in corporating many components; hence the reliability, availability and maintainability of this subsystem is considered as the subject of this study. For clarity it is titled hydraulic system.

Hydraulic system contains hydraulic cylinders, hydraulic pumps, hydraulic motors, hydraulic tank, oil filters, hydraulic gear boxes, hydraulic accumulators and Hydraulic power pack cooling circuit. These components

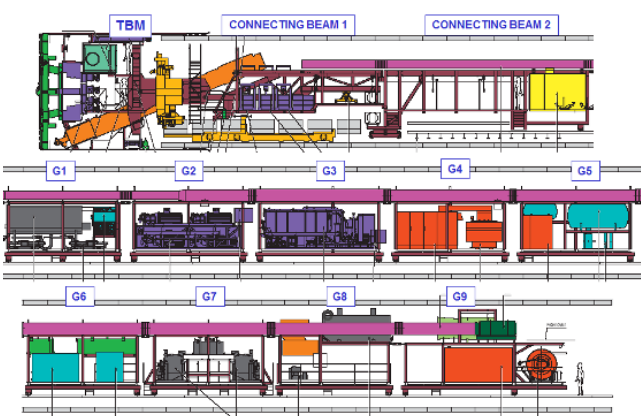

Figure 3. Schematic representation of a NFM- EPB machine[21].

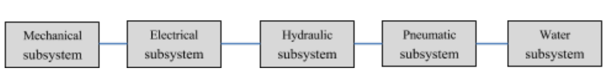

Figure 4. Main subsystems of an EPB-TBM[13].

are located in front part of the machine (TBM in Figure 3), connecting beams 1 & 2, gantries 1, 2 and 3. A brief description of hydraulic system of the NFM machine in line 1 of Tabriz metro is as follow:

The hydraulic powerhouse, situated on hydraulic skid, is mainly composed of:

- An oil tank with a capacity of 6m^3 equipped with a filtration unit and water/oil heat exchanger.
- A pump supplying hydraulic energy to the screw conveyor gate cylinders, safety gate cylinders and screw conveyor retraction cylinders.
- Two pumping units (4pumps) supplying hydraulic energy to the thrust cylinders and the articulation cylinders.
- Two pumping units supplying hydraulic energy to the erector cylinders and motorization.
- Three pumping units supplying hydraulic energy to the screw conveyor motors.
- A pumping unit supplying hydraulic energy to the segment conveyor table cylinders and to the bogies cylinder.
- A pumping unit (4 pumps) supplying hydraulic energy to the motors of the drive unit.

The grouting hydraulic skid is used to control and supply the electrically driven pumps for the mortar injection lines and the mixer in the mortar tank. The grouting hydraulic skid, driving by hydraulic power pack, is situated on gantry G1and mainly is composed of:

- An oil tank
- A pumping unit driving a motor that operates the agitators.
- A pumping unit ensuring circulation of the tank's oil for filtration and cooling.
- Pumping units driving the 2 mortar injection pumps.

The rotation of the cutter head is ensured by 8 hydraulic gear motors that drive a central slewing ring integrated in the cutter head. The tunneling machine's thrust is ensured by 22 cylinders distributed around 4 piloting sectors. The cylinders thrust force is transmitted to the segments by 11 pads shared by twin cylinders. There are two types of cylinders:

- Normal cylinders, cylinders with elongation sensors that allow the forward progress of the machine to be measured in real time. The information is displayed in the monitoring system in the control cabin.

- The cylinders which are powered by 1 hydraulic pump unit (including three hydraulic pumps), situated on gantry 2 of the backup train.

Articulation allows the front shield to be articulated with respect to the rear shield in an airtight manner to allow the tunneling machine to follow the curve of the tunnel. The articulation is composed of 9 hydraulic cylinders. The purpose of the erector is to grip, handle and position the segments to build up the rings. The segments are drawn to a loading station via the segment transport table by the backup train. The erector is composed of 2 main subassemblies: a rotation/lifting sub-assembly (2 degrees of freedom), a segment gripping table sub-assembly (3 degrees of freedom), these 2 sub-assemblies are supported by casing (rotor). This casing is mounted on the fixed framework of the erector (stator) by the intermediary of the slewing ring. The rotor is driven in rotation by a hydraulic motor, a pinion and a toothed annular gear fixed to the erector's stator (the rotation is limited to ± 220° by end of stroke detectors taken from encoder). While the segments are being positioned, the rotation supplied equals the torque required to compress the segment seals. The gripping table is mounted on the rotor using a cradle guided by two guide bars and moves radially with the help of two hydraulic cylinders[21].

Currently NFM-EPB machines are favorably used in construction of metro tunnels in Iran (e.g. Tabriz metro 2 machines, Mashhad metro 1 machine, Ahvaz metro 2 machines and Shiraz metro 2 machines which the latter project is completed), consequently RAM analysis of this type of EPB machine is necessary for civil engineers and Iranian tunneling association and companies.

4. RAM Analysis of Hydraulic System of EPB-TBM

In RAM analysis of any equipment or system, providing an appropriate field database of failure and maintenance data is important for getting reliable and accurate results[22].

4.1 Data Collection and Data Analysis

In this study, RAM analysis of hydraulic system of EPB-TBM is performed by collecting the failure and maintenance data of machine's hydraulic system from 2009-07-16 to 2011-09-28. These data were raw data that had already been collected by daily operation and boring reports of machine operator, shift supervisor and maintenance personnel, for some general information purposes. By sorting and arranging the data in a chronological order for applying statistical analysis, a data table was designed. A number of 47 failures for hydraulic system were recorded in the above mentioned period. After this stage, the TBFs and TTRs of hydraulic system were calculated (Table 1).

The basic methodology for analyzing reliability, availability and maintainability of the failure and repair characteristics of a repairable machine/system is offered by Ascheret al[22]. Failures and repairs of a repairable machine/system have been modeled on the basis of a renewal process, homogenous/non-homogenous Poisson process (NHPP), or a Power Law model[23,24]. In the renewal process, the TBFs and TTRs are assumed to be independent and identically distributed (iid) and failure or repair data are considered for analyzing by a suitable probability distribution function. For determination of the iid nature of failure/repair data, proper tests should be used to investigate the presence of trends and correlation in the failure/repair data. If there is no trend and correlation in present data, the assumption of iid for the TBFs or TTR sis satisfied.

The trend test can be performed using the method suggested in military test by calculating the test statistic form Equation (5):

$$U = 2\sum_{i=1}^{n-1} \ln \frac{T_n}{T_i} \tag{5}$$

Where, the data are failure-truncated at the n^{th} failure at time T_n. If this value is located between lower confidence level in Chi-square distribution $\chi^2_{0.05}$ and upper confidence level $\chi^2_{0.95}$, then the data have no trends[25]. The results showed that there is no trend in TBFs and TTRs data (Table 2).

The serial correlation test can be performed by plotting of the i^{th} TBF or TTR against $(i-1)^{th}$ TBF or TTR. If the plotted points are randomly scattered without any pattern, it can be interpreted that the TBFs or TTRs have no serial correlation[26]. Figures 5 and 6 demonstrate the results of correlation test in this study. As can be seen in these figures, there is no correlation in TBFs and TTRs. Therefore, the assumption that the data are IID is valid and classical statistical techniques is the best tool for reliability, availability and maintainability analysis.

Table 1. TBFs and TTRs of hydraulic system of studied TBM

Failure No.	TBF(h)	TTR(h)	Failure No.	TBF(h)	TTR(h)	Failure No.	TBF(h)	TTR(h)
1	0.5	0.5	17	64.83	0.33	33	190.33	0.5
2	37.5	1.5	18	101	1.33	34	13.5	0.17
3	23	0.33	19	139.83	1.17	35	143	1.83
4	0.33	1.33	20	179.83	1	36	0.67	1.17
5	47.83	2	21	3.5	6.5	37	148.67	0.33
6	9.5	2.83	22	28	0.67	38	30.17	3.67
7	31	3.5	23	76.17	0.17	39	16.83	0.33
8	154.5	2.67	24	43.33	0.33	40	1.67	2.1
9	6.5	2.33	25	23.33	0.33	41	82	2
10	65.17	0.33	26	39.17	0.17	42	100	0.67
11	83	0.67	27	25.33	0.33	43	13.33	3.67
12	198.67	0.67	28	30	0.33	44	1	2
13	38	1.17	29	4.17	0.17	45	137.83	6.33
14	15.5	2.17	30	39.33	2	46	32.83	0.5
15	0.83	2.5	31	60	1	47	15	6
16	67.5	0.33	32	0.83	0.33			

Table 2. Computed value of statistic U in analytical test on TBF and TTR data

Data	Number of failures	Degree of freedom	Calculated statistic U	Lower confidence level	Upper confidence level	Presence of trend
TBFs	47	92	112.4	55.2	95.1	70.9 < 112.4 < 115.4 No trend
TTRs	47	92	100.7	55.2	95.1	70.4 < 100.7 < 115.4 No trend

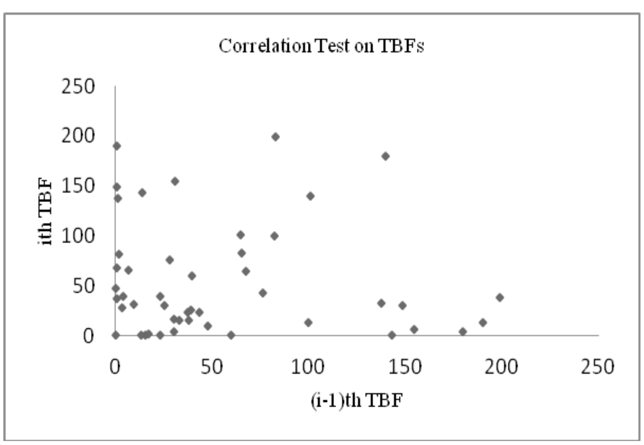

Figure 5. Serial correlation on TBFs.

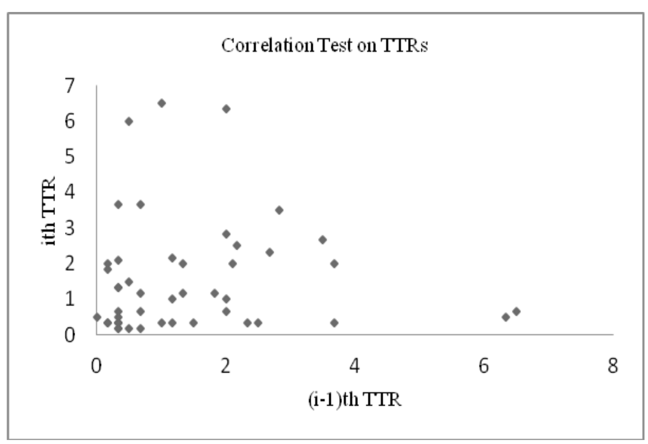

Figure 6. Serial correlation on TTRs.

4.2. Calculating the RAM of Hydraulic System of EPB-TBM

In this paper the Weibull++6 and Easy fit softwares were used for data analysis and finding the best-fit distributions. The Kolmogorov-Smirnov (K-S) test has been used for selecting the best distributions.

The result of data analysis, top five fitted and best-fitted distributions are illustrated in Table 3.

The reliability and maintainability functions for hydraulic system of studied EPB-TBM are calculated with the use of Equation (1), Equation (2) and the best-fitted distributions according to Table 3. The obtained functions for reliability (R_t) and maintainability (M_t) are as follow:

$$R(t)=1-\frac{1}{k\beta^{k\alpha}\Gamma(\alpha)}\int_0^t t^{k\alpha-1}e^{-\left(\frac{t}{\beta}\right)^k}dt=1-0.047\int_0^t t^{-0.242}e^{-(0.017t)^{0.883}}dt \quad (6)$$

$$M(t)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^t t^{\alpha-1}e^{-\frac{t}{\beta}}dt=0.596\int_0^t t^{-0.074}e^{-0.602t}dt \quad (7)$$

Furthermore, the achieved plots are illustrated in Figures 7 and 8.

According to reliability curve, the probability that hydraulic system of EPB-TBM is in operation for 20 h without failure is 60.7%. It takes approximately 30.16 h that the reliability of hydraulic system reduces to 50%.

Reliability analysis is one of the best ways for maintenance scheduling. The maintenance of an operating unit after failure is costly and its repairing may require a long time. Therefore, determining the preventive maintenance intervals for unit is important before it fails. Preventive maintenance includes scheduled checks and inspections of physical condition, fault diagnostics, measurement checks, scheduled shutdowns for opening and cleaning equipment, overhauling, etc. According to reliability plot, reliability-based preventive maintenance time intervals for hydraulic system of the machine were calculated. The reliability-based maintenance intervals for 90%, 80%, 70% and 50% reliability level are respectively 2.72, 7.17, 13.1 and 30.16 h. In many engineering operations, 80% is selected as the best practical value for efficiency and performance evaluation. Therefore, for having good and reliable operation, it is suggested that the hydraulic system of EPB-TBM should be checked and serviced before 7.17 h operation.

The calculations showed that Time To Repair (TTR) of this system varies from 0.17 h to 6.5 h with 1.54 h as Mean Time To Repair (MTTR). This means that the failures of hydraulic system EPB-TBM have had no long downtime. The maintainability plot demonstrated that a high percentage of failures have been repaired in less than 1 hour. There is 80% chance that the hydraulic system EPB-TBM in Tabriz metro tunnel repair be accomplished within 2.45 h. This means that with 80% probability the preventive maintenance will complete within 2.45 h.

Table 3. The results of data analysis and best-fit distributions

TBFs	K-S test	TTRs	K-S test
Gen. Gamma	0.08747	Gamma	0.12498
Weibull (3P)	0.09079	Exponential	0.12598
Gen. Extreme Value	0.70442	Weibull (3P)	0.12979
Gen. Logistic	0.85949	Lognormal (3P)	0.13197
Gamma	0.11211	Gamma (3P)	0.13747
Best fit	Parameters	Best fit	Parameters
Gen. Gamma	k = 0.883 α = 0.859 β = 58.556	Gamma	α = 0.926 β = 1.661

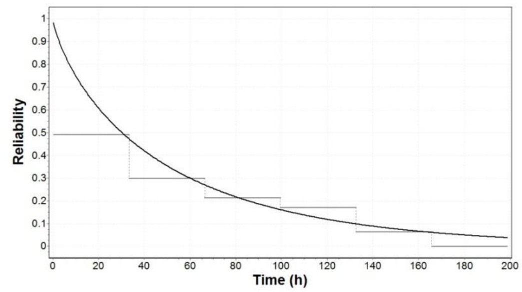

Figure 7. Reliability plot of hydraulic system of studied EPB-TBM.

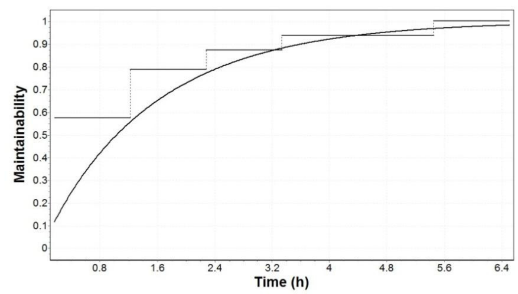

Figure 8. Maintainability plot of hydraulic system of studied EPB-TBM.

This value is a basic and important tool in operation and maintenance management. Maintenance or repair time may be reduced by proper planning and spare parts management for increased availability of the machine.

According to TBFs and TTRs the availability of hydraulic system of EPB-TBM in Tarbriz metro tunnel could be achieved. MTBF and MTTR were calculated as 54.57 h and 1.54 h respectively. Consequently, using Equation 4, the availability value is:

$$A = \frac{MTBF}{MTBF + MTTR} = \frac{54.57}{54.57 + 1.54} = 0.97$$

Having a low MTTR, the hydraulic system of EPB-TBM has a high availability. By calculating the availability of all of the machine subsystems, a new concept of the availability of EPB-TBM can be attained for time planning and cost control in such mechanized tunneling project.

5. Conclusions

Reliability, availability and maintainability analysis should be an essential part of tunnel engineering management for increasing availability and utility of tunnel boring machines. To improve the reliability, availability and maintainability of these machines, the most important measures requiring immediate attention are to grasp and remove the factors causing failures in all steps of the life cycle, such as planning, design, construction, and maintenance, and to evaluate quantitatively the RAM values based on the failure and repair history data. RAM analysis of hydraulic system of NFM EPB-TBM showed that the TBF and TTR data have generalized Gamma and Gamma distributions respectively.

The maintainability plot shows that a high percentage of failures have been repaired in a less than 1 hour. There is 80% chance that the hydraulic system EPB-TBM in Tabriz metro tunnel repair be accomplished within 2.45 h. This means that with 80% probability the preventive maintenance will complete within 2.45 h. According to MTBF and MTTR, the availability of hydraulic system of machine is 97%. Having a low MTTR, the hydraulic system of EPB-TBM has a high availability.

This study depicts that RAM analysis is very important for deciding about maintenance intervals. By calculating the availability of all of the machine subsystems, a new concept of the availability of EPB-TBM can be attained for time planning and cost control in mechanized tunneling projects. For having a reliable utilization factor of TBMs, it is suggested that downtimes due to geological condition, rock mass properties, unskilled operator and maintenance personnel, etc, be considered. In present research work, these downtimes are negligible and the skill of project personnel's is considered acceptable.

6. Acknowledgements

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