The Reliability and Maintainability Analysis of Pneumatic System of Rotary Drilling Machines

Mohammad Javad Rahimdel · Seyed Hadi Hosienie ·
Mohammad Ataei · Reza Khalokakaei

Received: 11 April 2013 / Accepted: 8 October 2013
© The Institution of Engineers (India) 2013

Abstract In any blasthole drilling the bottom of the blasthole must be kept clean by evacuating drill cuttings or it flushing as soon as they appear to ensure efficient drilling. If it is not done well, a large quantity of energy will be consumed in regrinding with the consequent wear on drill bit and decrease penetration, apart from the risk of jamming. Therefore, research on reliability and probability of safe operation of pneumatic system of drilling machines is of prime importance to ensure safe drilling operations. In this paper, reliability of this system was modeled and analyzed. To doing this research, drilling machines in Sarcheshmeh Copper Mine in Iran have been selected for data collection and analysis. After reliability modeling of pneumatic system, maintenance scheduling has been presented based on different reliability levels. There were four rotary drilling machines in this mine (named A, B, C and D). Results showed that after about 7 h drilling of machines A and B, and after 103 and 44 h drilling of machines C and D respectively, noticeably the reliability of pneumatic system reached to 80 %. As a result, machines C and D have more reliable pneumatic systems in comparison to machines A and B and checking and servicing of

pneumatic system before these time was essential. Also, maintainability analysis showed that more failures of pneumatic system of machines A, B, C and D will be noticeably repaired at about 28, 34, 6 and 9 h.

Keywords Rotary drilling machines · Pneumatic system · Reliability · Maintainability · Sarcheshmeh Copper Mine

Introduction

Mining equipment has an important role in increasing the production rate and safety. Because of high cost and complex technology of mining machinery, the maintenance is an important aspect and improving it for a few percent can help the mine managers in reducing the production costs.

Reliability analysis has been gradually accepted as a standard tool for the planning and operation of automatic and complex mining systems since the mid-1980s [1]. As yet, reliability of mine power system [2], mine production system [3], reliability of LHD machines [4–6], underground trucks [7], reliability of equipment in longwall faces [8] and reliability of double-drum shearer in longwall coal mining [9] have been studied and reported.

Drilling equipment is the most important operation unit in mine and mining industries and their failure can result in reduction in production and mining profitability. In any drilling operation, the bottom of the blasthole must be maintained clean by evacuating drill cuttings or flushing as soon as they appear to ensure efficient drilling. Compressed air is the invariable medium for flushing the blasthole. It plays a very important role in the drilling process because in many cases the power consumed by the air compressor on rotary blasthole drilling machines is more than the

M. J. Rahimdel (✉)
Faculty of Mining Engineering, Sahand University of
Technology, Tabriz, Iran
e-mail: mj.rahimdel@yahoo.com

S. H. Hosienie
Division of Operation and Maintenance Engineering, Lulea
University of Technology, Lulea, Sweden
e-mail: hoseiniesh@gmail.com

M. Ataei · R. Khalokakaei
Faculty of Mining Engineering, Petroleum and Geophysics,
Shahrood University of Technology, Shahrood, Iran
e-mail: Ataei@shahroodut.ac.ir

power consumed by any other of its devices like rotary head, feed mechanism, propel mechanism and etc. [10].

In this paper, after introducing the pneumatic system in the rotary drilling machines in Sarcheshmeh Copper Mine in Iran, reliability and maintainability of this system has been modeled and discussed.

Reliability and Maintainability Modeling

Reliability is the probability of equipment or processes to function without failure when operated correctly for a given interval of time under stated conditions. The mathematical definition of reliability is presented by Eq. (1) [10].

$$R(t) = 1 - F(t) = 1 - \int_0^t f(x)dx, \quad (1)$$

where $R(t)$ is the reliability at time t , $F(t)$ is cumulative failure distribution function and $f(x)$ is failure probability density function.

Maintainability is the ability of an item to be retained in, or restored to, a specified condition when maintenance is performed. In other words, maintainability measures the ease and speed with which a system can be restored to operational status after a failure occurs. The maintainability goal is that the system should be maintained without large investment of time, at the lowest cost, and with a minimum expenditure of resources. The maintainability function is defined by followed equation [11].

$$m(t) = \int_0^t f_r(x)dx, \quad (2)$$

where $m(t)$ is the maintainability function, t is time and $f_r(t)$ is the repair time probability density function.

For the reliability modeling of repairable systems the basic methodology is presented step-by-step in Fig. 1 [1]. It shows a detailed flowchart for model identification and is used here as a basis for the analysis of the failure data.

Selection of appropriate method to reliability modeling is the first step of the research. Three methods are generally used for reliability analysis of repairable systems: Renewal Process (RP), Homogeneous Poisson Process (HPP), and Non Homogeneous Poisson Process (NHPP). In PR method, analysis of data reliability is usually based on the assumption that the times between failures (TBF) are independent and identically distributed (iid) at the time domain. Trend test and serial correlation test are used for validation of this assumption [1].

The data sets can be analyzed for the presence of trends by using the test suggested in military hand book-189 by calculating the test statistic as follows:

Fig. 1 Reliability analysis process of a repairable system

$$U = 2 \sum_{i=1}^{n-1} \ln(T_n/T_i), \quad (3)$$

where the data are failure-truncated at the n th failure at time T_n .

Under the null hypothesis of a HPP, the test statistic U is Chi squared distributed with a $2(n-1)$ degree of freedom.

The presence of serial correlation can be tested by plotting the i th TBF against $(i-1)$ th TBF. If the plotted points are randomly scattered without any pattern, it can be interpreted that the TBFs are free from serial correlation.

Pneumatic System of Rotary Drilling Machines

The main compressor used in rotary blasthole drilling machines is oil-flooded rotary screw type. A compressor is directly driven by a high voltage and high power electrical motor. Technical properties of the main electrical motor and compressor of studied machines are listed in Table 1. As the two components are very heavy, they were transversely mounted at the center of the machine main frame for stability. This type of compressor is explained as following.

Screw compressors consist of one male and one female rotor as showed in Fig. 2. The male rotor has four lobes, whereas the female rotor has six grooves. Both the male and female rotors are drive to outside and in the opposite direction. When the groove of the female rotor is opened to the suction port, atmospheric air fills the groove enclosure formed by the casing of the rotors and the end flanges. As the male rotor rotates and the female rotor follows, the lobe of the male rotor intrudes into the female rotor groove at the front flange end. The male and female rotors are so machined that the gap between male and female rotors is very small. Further, it is filled with lubricant circulated

Table 1 Characteristics of main electrical motor and compressor of studied drilling machines

Model: DMH-1800 XL	
Main electrical motor	
Voltage (V)	6,600 ± 10 %
Frequency (Hz)	150 ± 5 %
Phase number	3
Pole number	4
Service factor	1.15
Power (HP)	600
Speed (RPM)	1,500
Gear box coupling (Ft.lbs)	16
Maximum altitude (Ft)	900
Ambient temperature range (°C)	−16 to 56
Compressor	
Screw compressor capacity (CFM)	1,150–2,400
Air compressor pressure (Psig)	110

Fig. 2 Screw compressor of drilling machines [12]

through the compressor housing for the purpose. Thus, air cannot escape through this gap. As the male rotor rotates further and female rotor follows, the contact between suction port and the female rotor groove is lost and the air in the female rotor is entrapped. Further rotation causes the reduction of volume of the groove between female rotor [12]. Further rotation causes contact between the groove filled with compressed air and the discharge port at the lower side of the compressor casing. The compressed air thus rushes completely into the discharge port.

Reliability Analysis

Failure Data Collection and Analysis

At the first step of this research, the TBF of pneumatic system of four drilling machines in Sarcheshmeh Copper

Mine was calculated over a period of 18 months. Then the trend and serial correlation tests had been done. The results of serial correlation tests and trend test are shown respectively in Fig. 3 and Table 2.

Reliability Modeling and Analysis

Trend and serial correlation tests are shown that the TBF data are iid, therefore, RP technique can be used for reliability modeling. The reliability of pneumatic system was calculated by the use of best-fitted distribution. Data analysis and finding the best-fit distributions were done using Easy Fit 5.5 software. The Kolmogorov–Smirnov (K–S) test has been used for selecting the best distributions for reliability analysis.

The results of data analysis with top six fitted and the best-fitted distributions are given in Table 3.

By using the Table 3 and Eq. (1), the reliability functions were calculated and illustrated by Eqs. (4) through (7). The achieved reliability plots for pneumatic system of machines were shown in Fig. 4.

$$R_{Mach.A}(t) = \exp\left(-\left(\frac{t-\gamma}{\beta}\right)^{\alpha}\right) = \exp\left(-\left(\frac{t-3}{93.94}\right)^{0.57}\right) \quad (4)$$

$$\begin{aligned} R_{Mach.B}(t) &= \frac{1}{\sqrt{2\pi}\sigma} \int_0^t \frac{1}{t} \exp\left(-\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right) dt \\ &= 0.288 \int_0^t \frac{1}{t} \exp\left(-\frac{(\ln(t)-3.457)^2}{7.35}\right) dt \end{aligned} \quad (5)$$

$$\begin{aligned} R_{Mach.C}(t) &= \frac{1}{\sqrt{2\pi}\sigma} \int_0^t \frac{1}{t} \exp\left(-\frac{(\ln(t)-\mu)^2}{2\sigma^2}\right) dt \\ &= 0.406 \int_0^t \frac{1}{t} \exp\left(-\frac{(\ln(t)-5.448)^2}{1.862}\right) dt \end{aligned} \quad (6)$$

$$R_{Mach.D}(t) = 1 - \frac{\Gamma(t/\beta)^{\kappa}(\alpha)}{\Gamma(\alpha)} = 1 - \frac{\Gamma(t/509.5)^{0.832}(0.797)}{\Gamma(0.797)} \quad (7)$$

As shown in Fig. 4, reliability of pneumatic system of four machines reached to zero after about 1,400 h operation. On the other hand, without considering any maintenance before this time, all of machines will be stopped due to complete failure of their pneumatic system. All of machines have similar reductive rate behavior in reliability but machines C and D have a lower reductive rate against others.

Also, after about 7 h operation of drilling machines, reliability of pneumatic system of machines A and B

Fig. 3 Results of serial correlation test on TBF data **Table 2** Computed value of the test statistic U for TBF

Machine	Number of failure	Mean	Standard deviation	Degree of freedom	Calculated statistic U	Rejection of null hypothesis at 5 % level of significance	Modeling method
A	39	174.05	224.17	76	110.55	Not rejected (>56.92)	RP
B	50	109.24	157.52	98	196.62	Not rejected (>76.12)	RP
C	24	387.50	480.20	46	66.51	Not rejected (>31.48)	RP
D	7	455.59	481.80	12	22.29	Not rejected (>5.23)	RP

reached to 80 %. Reliability of pneumatic system of machines C and D will reach to 80 % at about 103 and 44 h operation, respectively. This means that after these times onwards, the failure probability of pneumatic system increases than 20 %.

Maintainability Analysis

Repair Data Collection and Analysis

The maintainability analysis of pneumatic system of studied machines was the second stage of this study. For this purpose, the repair data were collected using field studies and repair reports which were available in mine office. The time to repair (TTR) was calculated for all machines and the main repair operations were classified and archived. After data collection, the statistical analysis was done on available TTR data. All data analysis was done as the same had been done on TBF data. Therefore, analytical method

was used to test the type of the distribution of TTR data. The computed values of the test statistic for repair data of the pneumatic system of studied machines are given in Table 4.

As a result, the assumption that the repair data of machines are trend free is valid for all machines. Also, the serial correlation test showed that the data are correlation free and therefore the TTR data are iid. Consequently, RP technique can be used for maintainability modeling. The maintainability of pneumatic system was calculated with the use of best-fitted distribution.

Maintainability Modeling and Analysis

As done in analysis of TBF data, the Easy Fit software was used for analysis of TTR data and finding the best-fit distributions. Also, the Kolmogorov–Smirnov (K–S) test was used for selecting the best distributions among the possible choices. The results of data analysis and best-fitted distributions are illustrated in Table 5.

Table 3 Results of the best-fit distribution for TBF data set

Distribution	Machine A K-S test	Machine B K-S test	Machine C K-S test	Machine D K-S test
Exponential	0.279	0.294	0.203	0.261
Weibull (3P)	0.127	0.114	0.187	0.338
Gen. gamma	0.154	0.106	0.230	0.176
Gamma	0.172	0.120	0.167	0.237
Weibull (2P)	0.128	0.080	0.139	0.203
Lognormal	0.127	0.076	0.124	0.207
Best distribution	Weibull (3P)	Lognormal	Lognormal	Gen. gamma
Parameters	$\alpha = 0.570$ $\beta = 93.94$ $\gamma = 3.0$	$\sigma = 1.917$ $\mu = 3.457$	$\sigma = 0.965$ $\mu = 5.448$	$k = 0.832$ $\alpha = 0.797$ $\beta = 509.50$

Using the calculated parameters for best-fitted distributions on TTR data, the maintainability plots of pneumatic system of studied machines were shown in Fig. 5.

Regarding to maintainability plots, maintainability of pneumatic system of machines A and B respectively reached to 81 and 78 % after 30 h repair operation. This means that pneumatic system in these machines is repaired at 30 h with 92 and 90 % probability, noticeably. Besides, after 28, 34, 6 and 9 h, the maintainability of pneumatic system of machines A, B, C and D will be equal to about 80 %. That is, more failures of pneumatic system of machines A, B, C and D will be noticeably repaired at about 28, 34, 6 and 9 h.

The machines A and B have passed about 18 years of operation, but the machines C and D are in about 12th year of operation. Therefore, the highest maintainability of machines C and D, and the lowest reliability of machines A and B seem reasonable because of the differences in their ages. As mentioned above, machines C and then D have maintainable pneumatic system compared to other machines.

Maintenance Scheduling

To keep a system in normal condition, proper maintenance becomes even more important during its serviced life. Maintenance was classified into two categories, corrective maintenance (CM) and preventive maintenance (PM). Normally, PM is more effective than CM because it is always to keep a system in an available condition so that the large loss caused by unpredictable fails can be avoided.

PM is the preventive action in maintenance that strives to reduce the likelihood of failure through the detection of identifiable potential failures in the equipment's physical condition, and thus attempts to avoid functional failure

Fig. 4 Reliability plots of pneumatic system of drilling machines

occurrences. This is done through scheduled checks and inspections of physical condition, fault diagnostics, measurement, scheduled shutdowns for opening and cleaning equipment, scheduled shutdowns for replacing worn components, and scheduled shutdowns for overhauling plant and equipment. These PM activities can be grouped into the following categories that are scheduled on run-time intervals [13]:

- *Physical checks* This includes scheduled checks of physical conditions, and fault diagnostics.
- *Measurement checks* These include measurement of physical conditions such as stress cracks, thickness tests, wear tolerances, etc., and scheduled shutdowns for opening and cleaning equipment.
- *Replacement shuts* This includes scheduled shutdowns for replacement of worn components, and scheduled shutdowns for overhauling plant and equipment.

Reliability approach is one of the best ways to schedule the maintenance operations. As a result, PM interval has

Table 4 Computed value of the test statistic U for TTR

Machine	Number of repair	Mean	Standard deviation	Degree of freedom	Calculated statistic U	Rejection of null hypothesis at 5 % level of significance	Modeling method
A	38	24.12	48.41	74	117.48	Not rejected (>55.17)	RP
B	51	35.71	90.59	100	172.26	Not rejected (>77.90)	RP
C	16	5.21	9.24	30	39.16	Not rejected (>25.83)	RP
D	17	7.08	11.23	16	31.97	Not rejected (>20.08)	RP

Table 5 Best-fit distribution for TTR data set

Distribution	Machine A K-S test	Machine B K-S test	Machine C K-S test	Machine D K-S test
Exponential	0.329	0.430	0.317	0.334
Weibull-3P	0.088	0.098	0.216	0.218
Gen. gamma	0.176	0.194	0.317	0.265
Gamma	0.227	0.341	0.399	0.251
Weibull-2P	0.093	0.135	0.186	0.248
Lognormal	0.087	0.094	0.136	0.198
Best distribution	Lognormal	Lognormal	Lognormal	Lognormal
Parameters	$\sigma = 1.797$ $\mu = 1.806$	$\sigma = 1.963$ $\mu = 1.855$	$\sigma = 1.121$ $\mu = 0.828$	$\sigma = 1.439$ $\mu = 0.987$

Fig. 5 Maintainability plots of pneumatic system of machines

been estimated with regard to the reliability model to achieve suitable machine performance.

In many engineering operations, 80 % was selected as the best practical value for efficiency and performance evaluation. So, in this paper the 80 % was selected as the desired reliability level for scheduling the PM. Consequently, it was suggested that the pneumatic system of machines A and B should be checked and serviced approximately after every 7 h operation to have a good and reliable operation. This time is suggested at 100 and 45 h respectively for machines C and D. Reliability-based PM

Table 6 Reliability-based maintenance interval for 80 % reliability level

Machine	A	B	C	D
Time interval (h)	6.77	6.32	103.08	44.04

time intervals for pneumatic system of all of drilling machines are calculated and presented in Table 6.

Considering to Table 4, 24.12 and 35.71 h were calculated as mean time to repair (MTTR) for machines A and B, respectively. Also, maintainability analysis showed that the failures of pneumatic system of machines A and B had long downtime. Besides, it was suggested that pneumatic system of these machines should be checked and serviced after every 7 h operation. As a result, it was proposed that pneumatic system of these machines should be under overhaul repair before it starts operating normally to have good and safe operation of machines A and B.

Conclusions

In this paper, after introducing pneumatic system of rotary blasthole drilling machines, reliability and maintainability of this system were modeled and discussed as a case study;

drilling machines in Sarcheshmeh Copper Mine, namely machines A, B, C and D. Results of our calculations and analysis are given at the following:

- Time between failures (TBF) of machines B and C obey the log-normal distribution and TBF of machines A and D obey the weibull (3P) and gamma generalized distributions, respectively.
- Pneumatic system of drilling machines in Sarcheshmeh Copper Mine will be stopped at about 1,400 h. Also, machines C and then D have the highest reliable pneumatic system against other machines.
- There is 80 % chance that the pneumatic system of machines A, B, C and D repair will be noticeably accomplished at 28, 34, 6 and 9 h.
- To have a good and reliable operation, it is suggested that the pneumatic system of machines A and B should be checked and serviced every 7 h. This time interval for machines C and D were suggested at 100 and 44 h operation respectively. Also, it was suggested that pneumatic system of machines A and B should be under overhaul repair before it starts operating normally.

Acknowledgments The authors would like to thank R&D office of Iranian National Copper Company for its financial support and help during the field studies in Sarcheshmeh Copper Mine. The cooperation of managers and employees of Sarcheshmeh Copper Mine is also acknowledged.

References

1. J. Barabady, U. Kumar, Reliability analysis of mining equipment: a case study of a crushing plant at Jajarm bauxite mine in Iran. *Reliab. Eng. Syst. Saf.* **93**, 647–653 (2008)
2. E.K. Stanek, S.S. Venkata, Mine power system reliability. *IEEE Trans. Ind. Appl.* **24**(5), 818–819 (1988)
3. U. Kumar, Y. Huang, Reliability analysis of a mine production system-a case study, in *Proceedings Annual Reliability and Maintainability Symposium*, Atlanta, GA, USA, 1993, pp. 167–172
4. U. Kumar, Reliability analysis of load-haul-dump machines. PhD Thesis, Lulea University of Technology, Lulea, Sweden, 1990
5. D. Kumar, B. Klefsjo, U. Kumar, Reliability analysis of power transmission cables of electric mine loaders using the proportional hazards model. *Reliab. Eng. Syst. Saf.* **37**, 217–222 (1992)
6. U. Kumar, B. Klefsjö, Reliability analysis of hydraulic system of LHD machine using the power law process model. *Reliab. Eng. Syst. Saf.* **35**, 217–224 (1992)
7. R.A. Hall, L.K. Daneshmend, Reliability modeling of surface mining equipment: data gathering and analysis methodologies. *Int. J. Min. Reclam. Environ.* **17**(3), 139–155 (2003)
8. S.K. Mandal, P.K. Banik, Evaluation of reliability index of longwall equipment systems. *Min. Technol.* **78**, 138–140 (1996)
9. S.H. Hoseinie, M. Ataei, R. Khalokakaie, B. Ghodrati, U. Kumar, Reliability analysis of drum shearer machine at mechanized longwall mines. *J. Qual. Maintenance Eng.* **18**(1), 98–119 (2012)
10. C.L. Jimeno, E.L. Jimeno, F.J.A. Carcedo, *Drilling and Blasting of Rock* (A.A. Balkema, Rotterdam, 1995), pp. 87–91
11. B.S. Dhillon, *Mining Equipment, Reliability, Maintainability and Safety* (Springer Series in Reliability Engineering, London, 2008), pp. 18–50
12. V.G. Gokhale, *Rotary Drilling and Blasting in Large Surface Mines* (CRC/Balkema, Leiden, 2011), pp. 231–257
13. B.S. Dhillon, *Engineering Maintainability*, (Golf, 1999), pp. 355–365