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RELIABILITY ANALYSIS OF DRILLING OPERATION IN OPEN PIT MINES

ANALIZA NIEZAWODNOŚCI URZĄDZEŃ WIERTNICZYCH WYKORZYSTYWANYCH W KOPALNIACH ODKRYWKOWYCH

Considering the high investment and operation costs, reliability analysis of mining machineries is essential to achieve a lean operation and to prevent the unwanted stoppages. In open pit mining, drilling, as the initial stage of the exploitation operations, has a significant role in the other stages. Failure of drilling machines causes total delay in blasting operation. In this paper, the reliability of drilling operation has been analyzed using the Markov method. The failure and operation data of four heavy rotary drilling machines in Sarcheshme copper mine in Iran have been used as a case study. Failure rate and repair rate of all machines have been calculated using available data. Then, 16 possible operation states have been defined and the probability of being of drilling fleet in each of the states was calculated using Markov theory. The results showed that there was 77.2% probability that all machines in fleet were in operational condition. It means that, considering 360 working days per year, drilling operation will be in a reliable condition in 277.92 days.

Keywords: open pit mines, drilling machine, reliability, Markov

Biorąc pod uwagę wysokość kosztów inwestycyjnych a także eksploatacyjnych, przeprowadzenie analizy niezawodności maszyn i urządzeń górniczych jest sprawą kluczową dla zapewnienia sprawnego działania i dla wyeliminowania niepożądanych przestojów. W kopalniach odkrywkowych prace wiertnicze prowadzone w początkowych etapach eksploatacji mają ogromne znaczenie również w późniejszych fazach działalności przedsięwzięcia. Awaria urządzeń wiertniczych powoduje opóźnienia przy pracach strzałowych. W pracy tej przeanalizowano niezawodność urządzeń wiertniczych w oparciu o metodę Markowa. Jako studium przypadku wykorzystano dane zebrane w trakcie eksploatacji i awarii czterech obrotowych urządzeń wiertniczych wykorzystywanych w kopalni rud miedzi Sarcheshme w Iranie. Awaryjność maszyn i zakres oraz częstość napraw obliczono na podstawie dostępnych danych. Zdefiniowano 16 możliwych stanów działania, a prawdopodobieństwa znalezienia się jednego z urządzeń wiertniczych w każdym z podanych stanów obliczono z wykorzystaniem teorii Markowa. Wyniki pokazują, że poziom

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prawdopodobieństwa tego, że wszystkie urządzenia wiertnicze znajdować się będą w stanie gwarantującym ich właściwe działanie wynosi 77.2%. Biorąc pod uwagę 360 dni roboczych w roku, oznacza to, że prace wiertnicze prowadzone być mogą w warunkach niezawodności przez 277.92 dni w roku.

Słowa kluczowe: kopalnie odkrywkowe, urządzenia wiertnicze, niezawodność, Markow

1. Introduction

Drilling is the first operation in mine blasting and is one of the most important of mining operations. Mechanical, thermal, hydraulic, sonic, chemical, electrical, seismic and nuclear drilling are the types of drilling systems which have been used so far. Nowadays, mechanical drilling is known as the most applied drilling method in mining and civil engineering projects. The main components of this drilling system are; the drilling rig which is the source of mechanical energy, the drill rode which is the means of transmitting the energy, the bit which is a tool that exercises that energy upon the rock, and the flushing air that cleans out and evacuates the drilled chips. Rotary-percussion and rotary drilling are two main mechanical drilling methods which are used in open pit mining. Rotary-percussive rigs are used in all types of rocks and are classified in two large groups, depending upon where the hammer is located: top hammer and down-the-hole hammer. Nowadays, rotary drills with top hammer are used in surface mines and in large size quarries for drilling the soft and medium to hard formations.

This research aimed to be a study on the rotary drilling machines' operational structure and define the main manageable subsystems of this important mining machine. A fleet of four rotary drilling machines in Sarcheshmeh copper mine in Iran was studied. The reliability analysis was done using Markov theory.

2. Rotary drilling machine

All the rotary drilling machines are composed of similar operational construction units and are made by putting together many assemblies. These assemblies are very costly and have many small parts. Assemblies mounted on a rotary blasthole drilling machines have specific purposes as listed in Table 1. Various available machines (manufactured by different companies) have differences only in their technical characteristics, e.g. power and capacity. All the drilling machines are composed of similar operational construction units, such as, drive and feed unit, transmission, electric system block, compressor and pneumatic system, drilling assembles, hydraulic pumps and motors, oil tank and hydraulic system. Various available machines (manufactured by different companies) have differences in their technical characteristics, e.g. power and capacity. In this paper, according to the operation manuals of the drilling machine and maintenance reports and field observations, five main subsystems were defined. These are connected in series configuration and were for the first time applied to a drilling machine; hydraulic subsystem, electrical subsystem, pneumatic subsystem, drilling assembles (will be called drilling subsystem) and crawler assembles (will be called transmission subsystem). A typical hydraulic rotary blasthole drilling machine and its subsystems are presented in Figure 1.

TABLE 1

Assemblies mounted on a rotary blasthole drill (Gokhale, 2011)

Assembly	Purpose
Undercarriage	Undercarriage enables the movement of the machine from one hole to the other or in some cases from one worksite to the other.
Main Frame	Excepting the undercarriage all the other assemblies of a rotary blasthole drill are mounted on the top of a very sturdy frame called main frame.
Leveling Jacks	Leveling jacks, attached to the main frame, are meant for leveling the machine after it moves to the location of the hole to be drilled.
Prime Mover	A prime mover is the main source of power. All the driven components in the machine are driven by use of this power source so that they generate desired movements of the components. Diesel engines are used as prime movers in many drills. In some very large rotary blasthole drills electric power supplied to the mine is directly supplied to the drill from where it is distributed to various components.
Air Compressor	Air compressor is meant for compressing the atmospheric air to a preset pressure and circulating it to the bottom of the hole through the drill string components for flushing the blasthole and removing cuttings formed in the process of formation fracture.
Operator Cab	Operator's cab, located at the rear of a rotary blasthole drill, has all the necessary devices for observing and controlling all the necessary operations required to be performed during the process of drilling blastholes.
Driver Cab	In truck mounted rotary blasthole drills the operator's cab is located at the rear end. It is, therefore, not suitable for moving the drill on the road over long distance at higher speeds. In such case a separate driver's cab on the front – just like that of a heavy truck – becomes essential.
Mast	Mast accommodates the rotary head assembly and the feed force mechanism that enables linear movement of the drill head with necessary feed force. By suitably aligning the mast in vertical or angled position, drill string can be moved and blasthole can be drilled in the intended blasthole alignment.
Auxiliary Winch	Most of the rotary blasthole drills are equipped with a winch. Its wire rope enables handling the heavy accessories from the top of the mast.
Rotary Head	Rotary head rotates the drill string at desired rotary speeds by exerting the required torque.
Pipe Rack	Pipe Rack – also known by many different names – is built into the mast. It enables storing and adding or removing the drill pipes to the drill string mechanically. This gives speed and accuracy in the operations.
Hydraulic System	Only a hydraulic system is capable of generating linear motion with very high force required for such operations as mast raising/lowering, leveling the machine by hydraulic jacks etc. Every blasthole drill, therefore, consists of hydraulic systems. Besides, in many rotary blasthole drills, hydraulic system also supplies high pressure hydraulic oil to many hydraulic motors to generate rotary motion.
Dust Control Equipment	During drilling operation, huge quantity of very fine dust is generated at the bottom of the hole. It is ejected out of the hole with the circulating compressed air. To prevent such dust from mixing with the atmosphere and polluting it, a dust hood is provided on the drill. However, due to many reasons the dust hood proves insufficient in preventing mixing of the dust with atmosphere. This makes it essential to incorporate dust control equipment in a blasthole drill. It is of two types viz. Water injection or Dry dust control.
Machinery House	Machinery house is an enclosure that shelters many components and assemblies within it so as to protect them from heat, cold, rain, dust and flying rocks. It also creates pleasant surroundings to the personnel to safely repair or replace the components.

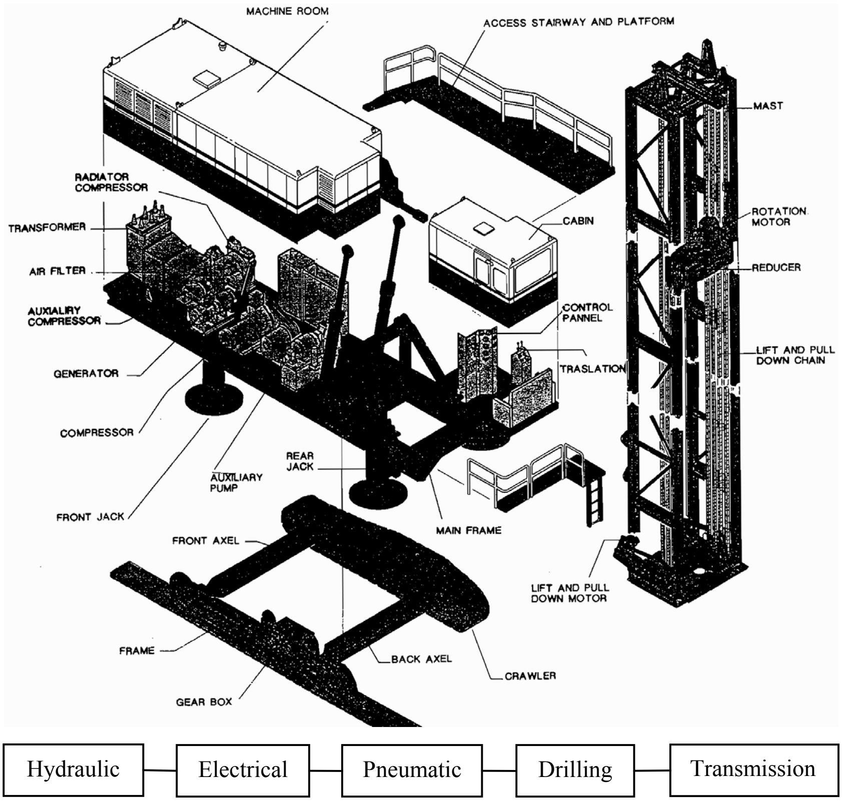

Fig. 1. Block diagram of rotary drilling machin

3. Methodology

In this paper, a Markov chain reliability analysis is proposed. In the probability theory, a stochastic process, given the present state, depends only on the current state, i.e. it is conditionally independent of the past states (the path of the process). Given present state which can be applied to the random behavior of system can vary discretely or continuously with respect to time and space. The discrete case generally is known as a Markov chain and Markov process is generally known for the continuous one (Birolini, 2007). A Markov chain is a special case of Markov process. It is used to study the short-run and long-run behavior of certain stochastic system (Taha, 1992). It is important to remember the role of the probabilities of changing state which are dependent only on the state itself in Markov theory (Smith, 2001).

As mentioned above, outcomes of successive observation of some characteristics of a certain population may be represented by Markov chain. The aim of the presented methodology is to introduce an approach to evaluate the reliability of the drilling machines and finally the reliability of drilling operation in the open pit mine using failure rate and repair rate of the machines. Therefore, collecting two kinds of data was necessary; firstly, the number of the working drilling machines and those which are under repair, and secondly the knowledge about the probabilities of the events. The essential probabilities which should be calculated are; the probability of the failure of a working machine (as a failure rate) and the probability of repairing of out of work machine (as a repair rate).

Based on the above assumptions, the active and out of work machine are modeled as a stochastic process. The reliability of the drilling operation is then estimated using Markov chains theory in which the probability of failure or a repair is not dependent on the past history of the system.

Regarding the described methodology, suppose that a drilling operation consists of "*m*" active machine as working ones. When an active machine is failed, number of active machines will be decreased to "*m*-1". This process is continued until all of active machines will be failed finally.

The explained states above then form a stochastic process. Figure 2 illustrates an example of the state spaces of such system. The first state (*S*1) shows a condition in which all *m* machine are working and none of them is out of work. In the second state (*S*2), one of the machines has been failed. Clearly in this state, there are *m*-1 machines still working as before and one machine has been failed. If the failed machine is repaired, and no other working one fails mean while then the system will be turned back to the previous state; otherwise, it will be remained in the same state or in case of more casualties it will go to the next states. This process will be continued until all of active machines are failed. In this circumstance, the system may remain in the final state which has been shown as *Sf* state in Figure 2.

So, with calculating the probability of occurrence stages which all of machines is failed, reliability estimation of drilling operation will be possible in conditions that all of machines are active.

States	S_1	S_2	S_3	S_{f-1}	S_f
Active Machine	m	m-1	m-2	1	0
Out of work machine	0	1	2	m-1	m

Fig. 2. Illustration of the different states paces

4. Reliability Analysis- a case study

In this section, stochastic process is used to model and analyze the drilling operation in Sarcheshme copper mine using Markov chains. Sarcheshmeh copper mine is located in south-east of Iran and is the largest open pit mine of Iran. The annual production of the mine is 14 million tons. A fleet of four electrical rotary drilling machines are used in this mine. Two of the studied machines are shown in Figure 3.

In this case study, the data was collected base on the failure and maintenance of drilling operation in 24 months. Based on statistical analysis, the accessibility of each machine when they were in an appropriate condition was 5.5 to 6.5 hours a month. So, the utilization of each machine was 75 percent in average. Since drilling operation was done in two shifts (16 hours), total operation hours of drilling in one month was 360 hours (= $0.75 \times 16 \times 30$). Moreover, statistical analysis showed that since electric current was off for 8 hours in one month in average, the probability of electric black out was 0.0222 (= 8/360).

After data collection, the failure and repair probability of all subsystems and finally of drilling machines were calculated as shown in Table 2. According to Table 2, hydraulic subsystem

Fig. 3. Two of the studied drilling machines in Sarcheshmeh copper mine-Iran

had the highest failure rate (probability of failure) among machines A, C and D. In machine B, pneumatic subsystem showed the highest failure rate. Therefore, these subsystems, specially the hydraulic one, should be noticed and checked more than other subsystems to improve the drilling operation and increase the reliability.

Figure 4 shows the different stages four of drilling machines. For each of the stages, two condition of active and failure exists from right to left respectively. As this figure shows, in S_1 state, as a sub category of α position, all of the four drilling machine were active and none of them had any repair. S_2, S_3, S_4 and S_5 are the states in the second position (β). In β position, one of the four drilling machines was out of work. In the γ position (S_6, S_7, S_8, S_9, S_{10} and S_{11} states), two drilling machines were out of work and only two of them were active. S_{12}, S_{13}, S_{14} and S_{15} are states in the fourth position (δ). In this stage, only one of machines was active. At last, the fifth position (η) indicated the S_{16} state where all of the drilling machines had been failed and no one was active. The mentioned states (S_1 to S_{16}) produce a Markov chain and hence the probability of the condition change of each machine from one state to alternative states can be calculated.

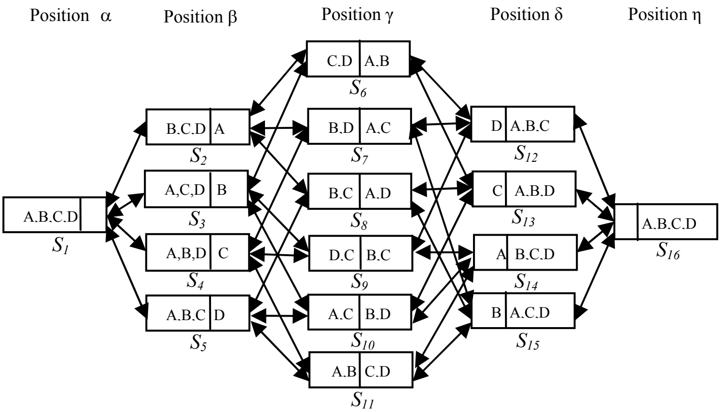

Fig. 4. Possible states for the active and under repair drilling machines

TABLE 3

Failure and repair probability of studied fleet of drilling machines in Sarcheshmeh mine

1	2	3	4	5	6	7	8	9
Machine	Subsystem	Average of failure time in one month (hr)	Probability of failure (Column 3/360)	Probability of machine failure	Average of repair time in one month (hr)	Probability of being under repair (Column 6/360)	Probability of repairing (1-Column 7)	Drill probability of repairing
A	Hydraulic	97.717	0.2714	0.2714×0.2231 ×0.2653×0.1132 ×0.1334=2.426E-4 +0.022222 = 0.022465	34.863	0.0968	0.9032	0.9032×0.9565 ×0.9204×0.9768 ×0.9508 = 0.738483
	Electrical	80.309	0.2231		15.671	0.0435	0.9565	
	Pneumatic	95.500	0.2653		28.647	0.0796	0.9204	
	Drilling	40.750	0.1132		8.327	0.0231	0.9768	
	Transmission	48.027	0.1334		17.729	0.0492	0.9508	
B	Hydraulic	59.452	0.1651	0.1651×0.175 ×0.2676×0.0745 ×0.1064=0.6129E-4 +0.022222 = 0.022283	20.277	0.0563	0.9437	0.9437×0.9793 ×0.9098×0.9451 ×0.9668 = 0.768263
	Electrical	63.000	0.175		7.440	0.0207	0.9793	
	Pneumatic	96.333	0.2676		32.471	0.0902	0.9098	
	Drilling	26.833	0.0745		9.75	0.0549	0.9451	
	Transmission	38.305	0.1064		11.968	0.0332	0.9668	
C	Hydraulic	91.917	0.2553	0.2553×0.2278 ×0.0963×0.0635 ×0.0352=0.1252E-4 +0.022222 = 0.022235	16.521	0.0459	0.9541	0.9541×0.9780 ×0.9198×0.9870 ×0.9879 = 0.836866
	Electrical	82	0.2278		7.910	0.0220	0.9780	
	Pneumatic	34.687	0.0964		28.884	0.0802	0.9198	
	Drilling	22.875	0.0635		4.671	0.0130	0.9870	
	Transmission	12.667	0.0352		4.349	0.0121	0.9879	
D	Hydraulic	96.283	0.2675	0.2675×0.0947 ×0.1468×0.0785 ×0.0521=0.1521E-4 +0.022222 = 0.022237	15.476	0.0730	0.9270	0.9270×0.9914 ×0.9803×0.9814 ×0.9279 = 0.820417
	Electrical	34.083	0.0947		3.100	0.0086	0.9914	
	Pneumatic	52.833	0.1468		7.100	0.0197	0.9803	
	Drilling	28.250	0.0785		6.706	0.0186	0.9814	
	Transmission	18.750	0.0521		25.947	0.0721	0.9279	

In order to illustrate the calculation procedure, an example which shows what happens when the system goes from state one to state two, i.e. (S_1 to S_2) is explained in detail. It simply means that one of the drills has been failed. The probability of this event may be calculated by Bernouli Distribution as below:

According to Table 3, the failure probability of drill A and activation probability of drill B, C and D are; 0.022465, 0.977717 (= 1-0.022283), 0.977765 (= 1-0.022235) and 0.977863 (= 1-0.022237) respectively. Probability of going from state one to state two ($P_{S_1} \rightarrow P_{S_2}$), is calculated as following:

$$\mathrm{P}_{1 \rightarrow 2} = (P_{S_1} \rightarrow P_{S_2}) = 0.022465 \times 0.977717 \times 0.977765 \times 0.977863 = 0.020998$$

Obviously, $P_{1\rightarrow 2}$ stands for the second entry in the first row of transition matrix. It is obvious that the transition probability of states S_1 up to S_{16}, should obey the rules of Markov chain analysis; that is, the summation of the probabilities in each row of transition matrix should be 1 (see equation 1).

$$\sum_{i=1}^{16} P_{ij} = 1 \qquad\qquad j = 1, 2, \ldots, 16 \tag{1}$$

According to the described calculations, it is now possible to arrange the transition matrix. It is a square matrix, in which each row is a fixed probability vector that shows the probability of transition of the system from a certain state to an alternative state of the system. For example, the first row is a vector which its entries indicate the probabilities of transition of the state S_1 to the alternative states, including S_1 itself; hence, the probability of the event S_1 to S_1, i.e. P_{11}, appears in the first entry of the first row, where P_{1j} appears in the j^{th} column of the first row, meaning the probability of the event S_1 to S_j and so on. The matrix illustrated in Figure 5 is the transition matrix of the fleet of drilling machines in the studied mine. The numbers have been rounded to 4-desimal places.

$$P = \begin{pmatrix}
0.9166 & 0.021 & 0.0208 & 0.0208 & 0.0208 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.6903 & 0.2929 & 0 & 0 & 0 & 0.0056 & 0.0056 & 0.0056 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.718 & 0 & 0.2672 & 0 & 0 & 0.005 & 0 & 0 & 0.0049 & 0.0049 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.7821 & 0 & 0 & 0.2074 & 0 & 0 & 0.0035 & 0 & 0.0035 & 0.0035 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.7667 & 0 & 0 & 0 & 0.2218 & 0 & 0 & 0.0039 & 0 & 0.0038 & 0.0038 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.1921 & 0.1635 & 0 & 0 & 0.6418 & 0 & 0 & 0 & 0 & 0 & 0.0013 & 0.0013 & 0 & 0 & 0 \\
0 & 0.2092 & 0 & 0.1151 & 0 & 0 & 0.6739 & 0 & 0 & 0 & 0 & 0.0009 & 0 & 0 & 0.0009 & 0 \\
0 & 0.2051 & 0 & 0 & 0.1268 & 0 & 0 & 0.6661 & 0 & 0 & 0 & 0 & 0.0010 & 0 & 0.0010 & 0 \\
0 & 0 & 0.1853 & 0.1198 & 0 & 0 & 0 & 0 & 0.6933 & 0 & 0 & 0.0008 & 0 & 0.0008 & 0 & 0 \\
0 & 0 & 0.0001 & 0 & 0.0001 & 0 & 0 & 0 & 0 & 0.9980 & 0 & 0 & 0.0009 & 0.0009 & 0 & 0 \\
0 & 0 & 0 & 0.1279 & 0.1437 & 0 & 0 & 0 & 0 & 0 & 0.7272 & 0 & 0 & 0.0006 & 0.0006 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.0496 & 0.0320 & 0 & 0.0273 & 0 & 0 & 0.8909 & 0 & 0 & 0 & 0.0002 \\
0 & 0 & 0 & 0 & 0 & 0.0486 & 0 & 0.0353 & 0 & 0.0300 & 0 & 0 & 0.8859 & 0 & 0 & 0.0002 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0303 & 0.0340 & 0.0220 & 0 & 0 & 0.9135 & 0 & 0.0002 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0342 & 0.0384 & 0 & 0 & 0.0212 & 0 & 0 & 0 & 0.9060 & 0.0002 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0081 & 0.0091 & 0.0050 & 0.0059 & 0.9719
\end{pmatrix}$$

Fig. 5. Transition matrix of the fleet of drilling machines in studied mine

When the system goes from state S_i to state S_j in one step, the entry P_{ij}^{n} should be considered as the probability of the change of system changes from state *Si* to state *Sj* in exactly n-steps. These new numbers, such as P_{ij}^{n}, will arrange the entries of matrix P^n, so called n-step transition matrix. The matrix shown in Figure 6 is the rounded form of the preceding matrix *P*. The sequence of *n*-steps transition matrices P^n approaches to the matrix *F*, which its rows are the unique fixed probability vector *f*; hence, the probability P_{ij}^{n} that S_j occurs for sufficiently large *n* is independent of the original state *Si* and it approaches the component f_j of *F*. In this particular situation the matrix *F*, has been formed by *P* power to 6100, indicating a very quick convergence.

$$F = \begin{pmatrix}
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000 \\
0.772 & 0.0236 & 0.0223 & 0.0206 & 0.0209 & 0.0008 & 0.0006 & 0.0008 & 0.0007 & 0.1345 & 0.0007 & 0.0000 & 0.0011 & 0.0014 & 0.0000 & 0.0000
\end{pmatrix}$$

Fig. 6. Stationary matrix *F* (has been formed by *P* matrix power to 6100)

On the other hand, the stationary state of the Markov chain can alternatively be obtained by solving the following system of equation (2). Where, for each *i*, t_i is the probability of the event that the system remains in the state S_i.

$$(t_1, t_2, t_3, \ldots, t_{16}) \times \mathrm{P} = (t_1, t_2, t_3, \ldots, t_{16}), \qquad \sum_{i=1}^{16} t_i = 1 \tag{2}$$

Now, by solving the system of the equations for the transition matrix, the values of t_1 up to t_{16} will are the same as the values of a fixed row in the stationary matrix *F*. Here are the values:

$$t_1 = 0.772,\ t_2 = 0.0236,\ t_3 = 0.0223,\ t_4 = 0.0206,\ t_5 = 0.0209,\ t_6 = 0.0008,$$
$$t_7 = 0.0006,\ t_8 = 0.0008,\ t_9 = 0.0007,\ t_{10} = 0.1345,\ t_{11} = 0.0007,\ t_{12} = 0,$$
$$t_{13} = 0.0011,\ t_{14} = 0.0014,\ t_{15} = 0 \text{ and } t_{16} = 0$$

The above results showed that there was 77.2% probability that the fleet of drilling machines in Sarcheshmeh copper mine be in operation condition at any proposed time. This value has many differences with the probability of the other states. It means that the drilling operation in this case study is so reliable.

The mentioned values can be multiplied by the number of the working days (360 days per year). For example by multiplying the probability of state S_1 by 360, we find out that in 277.92 (» 278) days of a year all machines of drilling fleet were available and operation goes on properly.

5. Conclusions

The reliability of mining equipments is one of the most important aspects of mine production management. This paper proposed an approach based on the Markov chain theory and stochastic processes to evaluate the reliability of drilling operation in open pit mines. As a case study, reliability of drilling operation in Sarcheshme Copper Mine was studied. The failure and repair data was collected from the available fleet consist of four rotary drilling machines. The statistical analysis showed that the hydraulic is the most critical subsystem of drilling machines. The pneumatic system has the highest failure probability after the hydraulic system. Forming the transition and stationary matrixes and doing the related calculations showed that there is 77.2% probability that the fleet of drilling machines in Sarcheshmeh copper mine be in operation condition at any proposed time. This means that in 277.92 (» 278) days of a year all machines of drilling fleet are available and operation is reliable.

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