

Reliability Analysis of Hydraulic System of a Tunnel-Erecting Machine Based on Dynamic Fault Tree and Bayesian Network[†]

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Abstract: Prefabricated utility tunnels play an important role in modern urban infrastructure construction. However, prefabricated utility tunnel segments are heavy, and the hoisting conditions are complicated, resulting in increased requirements in terms of the reliability of the equipment used for the erection and paving of utility tunnels, especially the hydraulic system of tunnel-erecting machines. Therefore, in this study, we performed reliability analysis of the hydraulic system of a tunnel-erecting machine. First, the working principle of the tunnel-erecting machine and its hydraulic system is analyzed, and a Takagi-Sugeno (T-S) dynamic fault tree model is constructed using the T-S dynamic fault tree analysis method, which is further transformed into a Bayesian network (BN) model. Secondly, according to the failure probability of the root node, combined with the BN conditional probability table (CPT), the failure probability of the leaf nodes of the hydraulic system of the tunnel-erecting machine in each time period and task time is forwardly inferred. Then, through the quantitative analysis of the sensitivity parameters in the BN analysis method, the importance of the components in the system can be reflected. Finally, the posterior probability of failure of the root node of the hydraulic system is calculated through the reverse reasoning of the BN analysis method, and the sensitive components of the system are identified. The results show that the proposed method can determine the main factors affecting the hydraulic system of a tunnel-erecting machine and provide reference for the safe operation of such equipment, as well as system maintenance.

Keywords: tunnel-erecting machine; dynamic fault tree; Bayesian network; hydraulic system; reliability analysis



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1. Introduction

Utility tunnels are modern, intensive and scientific urban infrastructure that integrate various underground pipelines, such as heating, water supply and drainage, communication, etc. They are also equipped with intelligent detection, alarm and monitoring systems [1–3]. Prefabricated utility tunnels represent a new construction method. Compared with traditional cast-in-place tunnels, they have the advantages of shortening the construction period, saving labor and reduced environmental pollution. However, special equipment in the form of a tunnel-erecting machine is required to hoist lay the structure during the installation process. The hydraulic system realizes the movement of the crane and the lifting of each outrigger during the working process of the tunnel-erecting machine. In the actual working process, failure of the hydraulic system seriously affects the working efficiency of the tunnel-erecting machine. Therefore, it is of considerable significance to analyze the reliability of the hydraulic system of the tunnel-erecting machine.

Dynamic fault tree analysis (DFTA) and Bayesian network (BN) are basic methods that can be applied reliable analysis and fault diagnosis and have been widely studied and

applied [4,5]. In recent years, scholars have used DFTA and BN to analyze the reliability of construction machinery. Wu and Tao [6] performed a dynamic analysis of the hydraulic system of a loader based on the Takagi-Sugeno (T-S) model and used probability importance to judge the impact of the bottom event on the system. Li et al. [7] used the BN transformed from a fault tree to analyze the risk of well collapse accidents. Li et al. [8] used a T-S fuzzy fault tree to analyze the reliability of the hydraulic circuit of the outrigger of a truck crane. Wang et al. [9] analyzed the hydraulic system of shearer height adjustment based on the dynamic fault tree model and obtained the subtree with the highest probability importance. Chen et al. [10] carried out reliability analysis on fully hydraulically driven construction machinery based on evidence theory and BN and calculated the failure probability interval, root node importance and sensitivity interval of leaf nodes. In view of the problems of insufficient dynamic logic gates, inability to effectively express dynamic failure behaviors and limitations of polymorphic systems in traditional fault trees, DUGAN dynamic fault trees, T-S fault trees and other analysis methods, Yao et al. [11] introduced the T-S fault tree analysis method. Based on this extension, a T-S dynamic fault tree analysis method was proposed. BN can not only describe the polymorphism between systems and the logical relationship of uncertainty between events but can also implement bidirectional reasoning [6]. Fault tree analysis is effective for analysis of the causes of accident failures, where BN has outstanding advantages in the study of complex systems and the expression of multimodal variables and can accurately analyze and diagnose the causes of event failures.

In view of the complementarity of T-S dynamic fault trees and BN, in this study, we use a prefabricated gantry crane to analyze the reliability of the hydraulic system of a tunnel-erecting machine based on the dynamic fault tree analysis and Bayesian network (DFTA-BN) analysis method.

2. Working Principle of Hydraulic System of Tunnel-Erecting Machine

The investigated tunnel-erecting machine is composed of a main beam, front outriggers, middle outriggers, rear outriggers, an electrical system, a hydraulic system, crane, etc. The tunnel-erecting machine is shown in Figure 1.

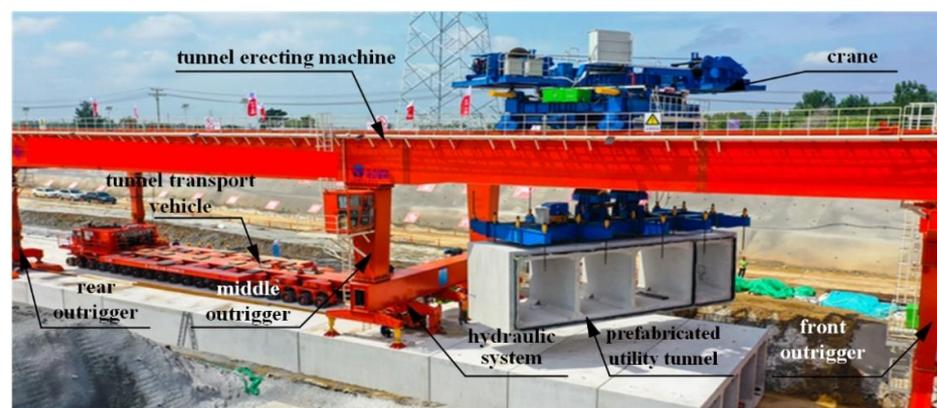
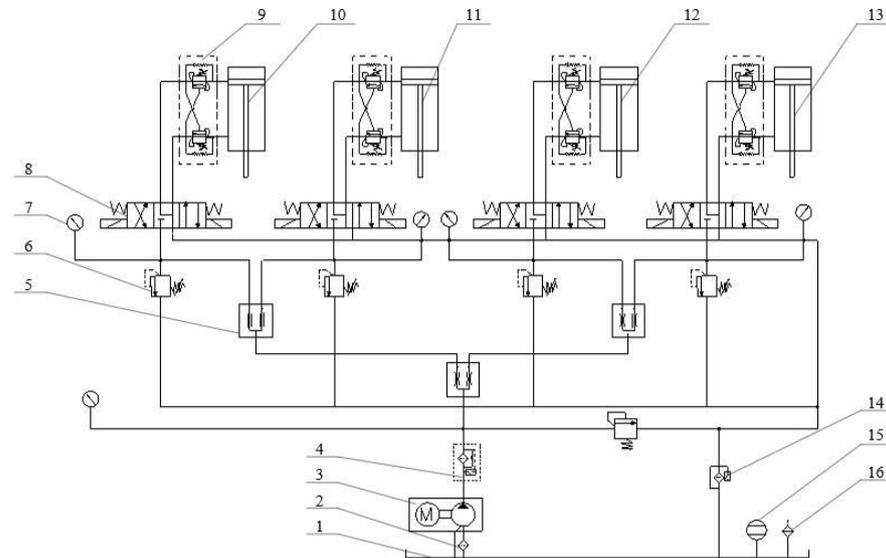


Figure 1. Tunnel-erecting machine for prefabricated utility tunnels.

The working principle of the hydraulic system is shown in Figure 2. Under the action of the oil pump motor unit, the pressure oil is shunted by a two-stage shunt valve and then flows to the crane traverse cylinder group, the front outrigger lifting cylinder group, the middle outrigger lifting cylinder group and the rear outrigger lifting cylinder group through the electromagnetic reversing valve. The diverting and collecting valve is used in each cylinder group to ensure that the same flow is delivered to each hydraulic cylinder, thus ensuring the synchronization of the expansion and contraction of each group of hydraulic cylinders and ensuring the smooth operation of the system. The relief valve unloading in the system can not only realize the constant pressure state of the system but also ensure the safe operation of the system. The system has a single-action function to

ensure that it can achieve independent action when synchronization errors occur. The two-way balance valve can prevent the hydraulic cylinder from falling over and ensure its smooth operation, with sufficient pressure-holding locking characteristics.



1 oil tank; 2 filter; 3 oil pump motor unit; 4 pressure oil filter; 5 diverter valve; 6 relief valve; 7 pressure gauge; 8 electromagnetic reversing valve; 9 balance valve; 10 crane hydraulic cylinder group; 11 Front outrigger hydraulic cylinder group; 12 Middle outrigger hydraulic cylinder group; 13 Rear outrigger hydraulic cylinder group; 14 Oil return filter; 15 Liquid level gauge; 16 Air filter

Figure 2. Principle diagram of the hydraulic system.

3. Construction of DFTA-BN Model of the Hydraulic System

3.1. DFTA Modeling of the Hydraulic System

Taking the hydraulic system of the tunnel-erecting machine as the research object, the established T-S dynamic fault tree model is shown in Figure 3. The intermediate events ($y_1 \sim y_9$) are gallery crane hydraulic system failure, hydraulic pump source failure, hydraulic component failure, oil pump motor unit failure, filter failure, hydraulic actuator failure, hydraulic control valve failure, jacking cylinder failure and traverse cylinder failure. The dynamic gates of $G_1 \sim G_9$ are all OR gates. The name and failure rate of the root node event are obtained by searching the data, as shown in Table 1.

Table 1. Basic event names and failure rates.

x_i	Basic Event Name	$\lambda_i (10^{-6}/h)$
x_1	Motor failure	6.8
x_2	Hydraulic pump failure	7.9
x_3	Auxiliary oil pump failure	7.9
x_4	Oil suction filter failure	0.8
x_5	Oil return filter failure	1.3
x_6	Fine filter failure	0.6
x_7	Insufficient fuel supply in the tank	1.3
x_8	High frictional resistance of the jacking cylinder	1.44
x_9	High back pressure of the return oil of the jacking cylinder	1.35
x_{10}	High friction resistance of the traverse cylinder	1.44
x_{11}	High back pressure of the traverse cylinder	1.35
x_{12}	Diverter valve failure	10.5
x_{13}	Balance valve failure	10.5
x_{14}	Relief valve failure	11.7
x_{15}	Solenoid valve failure	12.0
x_{16}	Poor guiderail lubrication	10.4

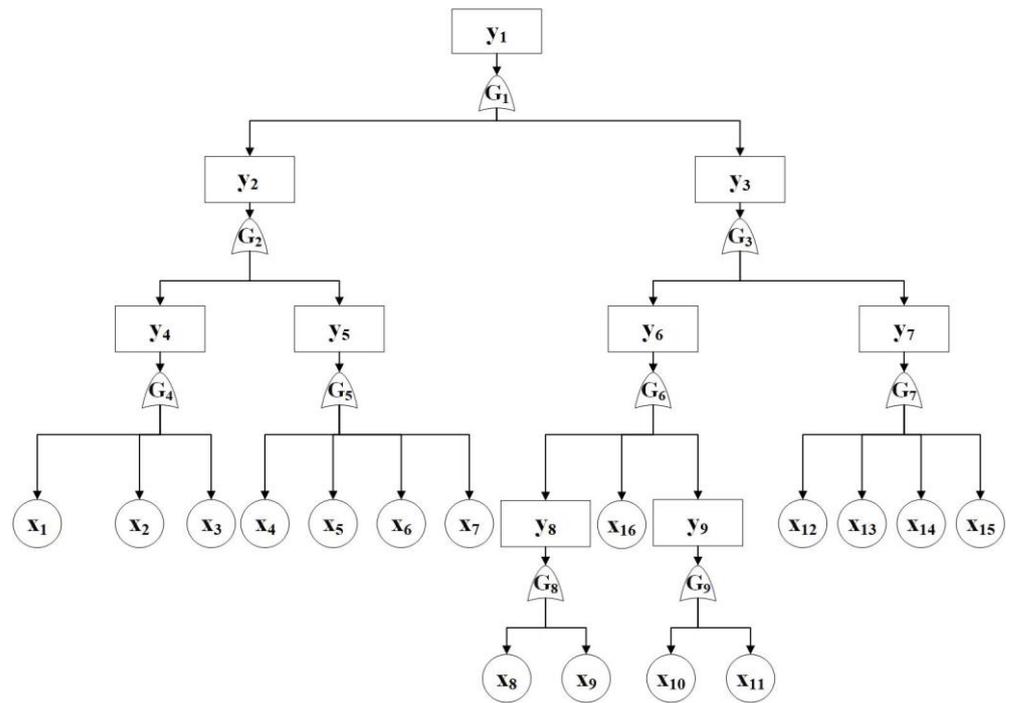


Figure 3. T-S dynamic fault tree.

3.2. BN Modeling of the Hydraulic System

According to the transformation method given by the basic event in the T-S dynamic fault tree corresponding to the root node of BN, the intermediate event corresponding to the intermediate node and the top event corresponding to the leaf node, the T-S dynamic fault tree is transformed into a BN directed acyclic graph, as shown in Figure 4. The conditional probability table (CPT) of the corresponding node of BN is obtained according to the T-S dynamic gate, and root nodes y_2 and y_3 represent the failure of the hydraulic pump source; the failure of hydraulic components are the main reasons for the failure of the hydraulic system of the gallery crane. The CPT of node y_1 is shown in Table 2.

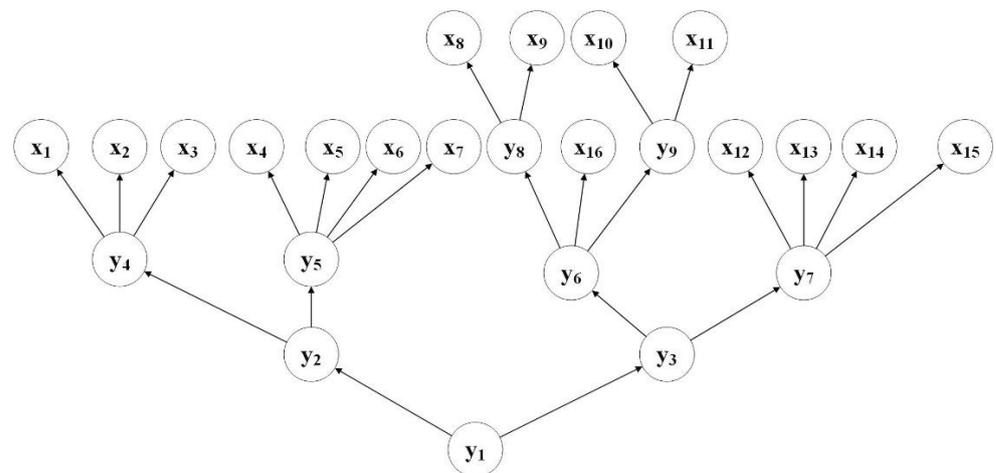


Figure 4. Directed acyclic graph.

According to the BN directed acyclic graph, sub-node y_1 and other sub-nodes undergo the same transformation process in CPT (not listed here).

Table 2. Conditional probability tables of y_1 .

Serial Number	y_2	y_3	$P(y_1^{[j_{y_1}]} = 1 y_2, y_3)$				
			1	2	3	4	5
1	1	1	1	0	0	0	0
2	1	2	1	0	0	0	0
3	1	3	1	0	0	0	0
...
25	5	5	0	0	0	0	1

4. Reliability Analysis of Hydraulic System Based on DFTA-BN

4.1. Node Failure Probability Reasoning

The failure probability of the leaf node is calculated according to the forward inference algorithm of BN. The task time ($T_M = 10,000$ h) is discretized and divided into an average of $m = 4$ segments, and the interval between each segment is $\Delta = 2500$. The time outside the task time is regarded as the fifth segment, and the fault state of the root node (x_i) in time segment j_i is $x_i^{[j_i]}$. The failure probability ($P(x_i^{[j_i]})$) is shown in Equation (1):

$$F_i t = 1 - e^{-\lambda_i t}$$

$$P(x_i^{[j_i]}) = \int_{(j_i-1)\Delta}^{j_i\Delta} f_i(t) dt = \int_{(j_i-1)\Delta}^{j_i\Delta} \frac{F_i(t)}{dt} dt \tag{1}$$

BN satisfies conditional independence. The system $X = \{x_1^{[j_1]}, x_2^{[j_2]}, \dots, x_n^{[j_n]}\}$ of n variables can be obtained according to the conditional independence of n variables. For any x_i exists $\pi(x_i^{[j_i]}) \subseteq \{x_1^{[j_1]}, \dots, x_n^{[j_n]}\}$, such that $x_i^{[j_i]}$ is the same as $\{x_1^{[j_1]}, \dots, x_n^{[j_n]}\}$ are conditionally independent. The probability joint distribution of n variables is shown in Equation (2):

$$P(X) = P(x_1^{[j_1]}, x_2^{[j_2]}, \dots, x_n^{[j_n]}) = P(x_1^{[j_1]}) P(x_n^{[j_n]} | x_1^{[j_1]}, \dots, x_{i-1}^{[j_{i-1}]}) = \prod_{i=1}^n P(x_i^{[j_i]} | \pi(x_i^{[j_i]})) \tag{2}$$

Due to conditional independence, the failure probability of child nodes can be passed. According to Equation (2), the joint probability when the child node ($y^{[j_y]}$) is 1 can be obtained as shown in Equation (3):

$$P(x_1^{[j_1]}, x_2^{[j_2]}, \dots, x_n^{[j_n]}, y^{[j_y]} = 1) = P(X, y^{[j_y]} = 1) = P(y^{[j_y]} = 1 | X) P(X) = P(y^{[j_y]} = 1 | X) \prod_{i=1}^n P(x_i^{[j_i]} | \pi(x_i^{[j_i]})) \tag{3}$$

The probabilities of leaf nodes in each time period are calculated as shown in Table 3.

Table 3. Failure rate of leaf node y_1 .

Period	Failure Rate
1	0.196163
2	0.157369
3	0.126729
4	0.102016

As shown in Table 3, the probability of failure of the oil pump motor unit and the diverter valve, balance valve, relief valve and electromagnetic reversing valve is high, and the probability of failure of the hydraulic system within the task time reaches 0.582277.

4.2. Posterior Probabilistic Inference

Posterior probability and reverse reasoning can be used to determine the factors that are prone to failure of the system through reverse reasoning so as to maintain and replace

them to ensure the normal operation of the system. The reverse reasoning of the root node in a two-state system is shown in Equation (4):

$$P(x_i^{[j_y]} = 1 | y^{[j_y]} = 1) = \frac{P(x_i^{[j_i]} = 1, y^{[j_y]} = 1)}{P(y^{[j_y]} = 1)} \tag{4}$$

The posterior probability of each root node in each time period and task time is obtained according to Equation (4), as shown in Table 4.

Table 4. Posterior probability of each root node.

x_i	Period					T_M
	1	2	3	4		
x_1	0.020338	0.024347	0.029442	0.035404		0.109530
x_2	0.024220	0.028967	0.034930	0.042130		0.130247
x_3	0.024220	0.028967	0.034930	0.042130		0.130247
x_4	0.002049	0.002499	0.003046	0.003714		0.011309
x_5	0.003328	0.004185	0.004950	0.006038		0.018500
x_6	0.001528	0.001863	0.002271	0.002769		0.008430
x_7	0.003328	0.004185	0.004950	0.006038		0.018500
x_8	0.003758	0.004586	0.005441	0.006798		0.020584
x_9	0.003540	0.004193	0.005264	0.006240		0.019237
x_{10}	0.003758	0.004586	0.005441	0.006798		0.020584
x_{11}	0.003540	0.004193	0.005264	0.006240		0.019237
x_{12}	0.033941	0.040602	0.048668	0.058313		0.181524
x_{13}	0.033941	0.040602	0.048668	0.058313		0.181524
x_{14}	0.038716	0.046314	0.055298	0.065984		0.206311
x_{15}	0.040037	0.047631	0.057100	0.067961		0.212729
x_{16}	0.033601	0.040185	0.047975	0.057688		0.179450

As shown in Table 4, the posterior probability values of root nodes $x_2, x_3, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}$ are large; that is, the basic events that is prone to failure of the system through reverse reasoning are the oil pump motor unit, diverter valve, balance valve, relief valve and electromagnetic reversing valve. When the hydraulic system fails, it can be checked, maintained and replaced as a priority to ensure the normal operation of the system.

4.3. Sensitivity Analysis

Sensitivity analysis is widely used in system feature analysis and abnormal feature discovery. Through sensitivity evaluation, it can identify high-risk events in the system, improve the reliability of the system and provide a basis for the formulation of security measures. In a two-state system, when y fails in the j_y time period, $S(x_i = 1, y^{[j_y]} = 1)$, as shown in Equation (5):

$$S(x_i = 1, y^{[j_y]} = 1) = \frac{I^{Pr}(x_i = 1, y^{[j_y]} = 1)}{\sum_{j_y=1}^m P(y^{[j_y]} = 1 | x_i = 1)} \tag{5}$$

The sensitivity ($S(x_i = 1)$) of the root node in the task time is shown in Equation (6):

$$S(x_i = 1) = \sum_{j_y}^m S(x_i = 1, y^{[j_y]} = 1) \tag{6}$$

As shown in Table 5, the sensitivity values of the root nodes $x_2, x_3, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}$ are relatively large, and the main oil pump, auxiliary oil pump, diverter valve, balance valve, relief valve, electromagnetic reversing valve, etc., are high-risk factors; thus, they should be checked and replaced to improve the reliability of the system.

Table 5. Sensitivity of each root node.

x_i	Period					T_M
	1	2	3	4		
x_1	0.092257	0.092724	0.093124	0.093505	0.371610	
x_2	0.107016	0.107543	0.107998	0.108440	0.430998	
x_3	0.107016	0.107543	0.107998	0.108440	0.430998	
x_4	0.011067	0.011125	0.011177	0.011227	0.044596	
x_5	0.017866	0.017964	0.018043	0.018124	0.071997	
x_6	0.008297	0.008340	0.008377	0.008415	0.033429	
x_7	0.017866	0.017964	0.018043	0.018124	0.071997	
x_8	0.019812	0.019920	0.020006	0.018831	0.078569	
x_9	0.018562	0.018663	0.018749	0.018826	0.074799	
x_{10}	0.019812	0.019920	0.020006	0.018831	0.078569	
x_{11}	0.018562	0.018663	0.018749	0.018826	0.074799	
x_{12}	0.141295	0.141963	0.142503	0.143044	0.568805	
x_{13}	0.141295	0.141963	0.142503	0.143044	0.568805	
x_{14}	0.156927	0.157652	0.158219	0.158787	0.631584	
x_{15}	0.160898	0.161609	0.162205	0.162770	0.647480	
x_{16}	0.139992	0.140653	0.141175	0.141725	0.563544	

5. Conclusions

The DFTA-BN analysis method not only makes up for the insufficiency of T-S dynamic fault tree operation and the inability of traditional BN to describe the fuzzy logic relationship between nodes but also solves the problems that the BN model and node CPT are difficult to construct and that the T-S dynamic fault tree cannot be reasoned in both directions.

The failure probability of the leaf nodes of the hydraulic system of a tunnel-erecting machine is derived through forward inference, and the BN posterior probability is used to infer the factors indicating system failure so as to maintain and replace it. Furthermore, the sensitivity of each root node is calculated, providing a reliable basis for equipment routine maintenance and fault diagnosis.

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