An Application of Fault Tree Analysis for Mobile Mooring System

Silvianita
PhD Student, Department of Civil Engineering,
Faculty of Engineering
Universiti Teknologi PETRONAS, Perak, Malaysia
Department of Ocean Engineering
Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
vian_nita@yahoo.com

Mohd. Faris Khamidi
Senior Lecturer in Department of Civil Engineering,
Faculty of Engineering
Universiti Teknologi PETRONAS, Perak, Malaysia

V.J. Kurian
Professor in Department of Civil Engineering,
Faculty of Engineering
Universiti Teknologi PETRONAS, Perak, Malaysia

Abstract— **Mooring system is an essential part of floating structures for station keeping. The objective of this paper is to determine the root cause of mooring system failure and to analyze the frequency of this failure. This paper developed the root cause of accident failure for mobile mooring system using Fault Tree Analysis (FTA). FTA is a deductive approach which is useful to breakdown the root causes of mooring system failure into undesired events. The main sub event failures of mobile mooring system are mooring line break, anchor failure, anchor handling failure and appurtenance connection failure. The result of this study will be useful to estimate the probabilities of the undesired failures in a system in order to handle the uncertainty condition and inadequate information.**

Keywords- Fault, Frequency, Mooring, Mobile, Tree.

I. INTRODUCTION

The mobile mooring system is an important sub system of floating structure, responsible for the positioning of offshore platform. Semi submersible platforms have been used for a variety of different activities such as drilling, pipe-laying, fire fighting, accommodation, crane operations and diving support [1]. Semi submersible platform have been used for several years as pipe lay vessels and the stability standards are not different from those applied to drilling units [2]. The platform used for this case study is a semi submersible column stabilized pipe lay barge fitted with 12 point mooring system to aid controlled movement during pipe lay operations. The vessel has a hull with four columns and two pontoons as illustrated in Fig. 1.

The pipe lay operation is associated with uncertainty especially in severe weather, the vessels need to continue pipe lay whilst still maintaining the ability to move the barge forward a sufficient distance to lower the pipeline to the seabed. In this condition it can lead to hazardous accidents that cause the project delay. In order to investigate the main accident hazards, the FTA method can be adopted.

FTA is one of the risk assessment methods that have been applied in various industries [3]. FTA has been used extensively to quantify the frequency of an accident based on logic diagrams. It is used to identify the possible causes of a top event [4-5]. FTA also used in prioritization and optimum resource allocation [6] and used to describe the customer selection for service analysis [7].

The aims of this paper are: (1) to determine the root cause of mooring system failure; (2) to analyze the frequency of mooring system failure.

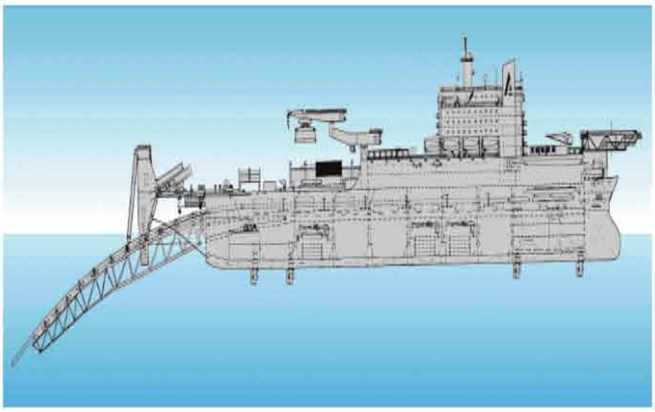


Figure 1. An illustration of semi submersible column stabilized pipe lay barge (Source: www.offshore-mag.com [8])

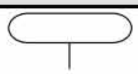
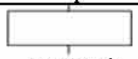
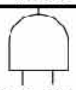
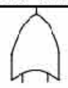
FTA has been widely use for generating the root cause of the undesired events in a system failure. In some situation the exact frequency of failure of events are available but sometimes in real operation it difficult to gather past exact failures data for FTA [9]. In order to evaluate the failure probability of mobile mooring system, failure rates of basic events must be known. In this study, the expert judgments are used to determine the probabilities of the basic events. The expert gives their judgment to describe a real world situation, experience and knowledge based on IMO (International Maritime Organization) standard as seen in Table I [10].

TABLE I. FREQUENCY INDEX

FI	Frequency	Definition	F (per ship year)
7	Frequent	Likely to occur once per month on one ship	10
5	Reasonably probable	Likely to occur once per year in a fleet of ships, i.e. likely to occur several times during a ships life	0.1
3	Remote	Likely to occur once per year in a fleet of 1000 of ships, i.e. 10% chance of occurring in the life of 4 similar ships	10^{-3}
1	Extremely remote	Likely to occur once in 100 years in a fleet of 1000 ships, i.e. 1% chance of occurring in the life of 40 similar ships	10^{-5}

FTA is generated of a number of symbols which are described in Table II [11]:

TABLE II. FTA SYMBOLS

Primary Event Symbols	
 Ellipse	Top Event : Description of the system level fault or the undesired event.
 Rectangle	Fault Event: Description of a lower level fault.
 House	Input Event: A normal system operating input which has the capability of causing a fault to occur.
 Circle	Basic Event: A failure at the lowest level of examination which has the capability of causing a fault to occur.
 AND Gate	Output occurs only if all inputs exist
 OR Gate	Output occurs only if one or more of the input events occur

Fault Tree Analysis (FTA) is deductive approach begins with a defined undesired event, usually a postulated accident condition and systematically considers all known events, faults, and occurrences which could cause or contribute to the occurrence of the undesired event [12]. Demerit and merit of this approach can be seen in Table III, [10]:

TABLE III. MERIT AND DEMERIT OF FTA

Merit	Demerit
Widely used & well accepted	Complicated and time consuming
Suitable for many hazards in QRA that arise from a combination of adverse circumstances	Analysts may overlook failure modes and fail to recognize common cause failures.
It is often the only technique that can generate credible likelihoods for novel, complex systems.	The diagrammatic format discourages analysts from stating explicitly the assumptions for each gate.
It is suitable for technical faults and human errors	All events are assumed to be independent
It a clear and logical form of presentation	It loses its clarity when applied to systems that do not fall into simple failed or working states

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II. FAULT TREE MATHEMATICS METHODOLOGY

The basic mathematical technique involved in the quantitative assessment of fault trees is called probability theory. It defines an analytical treatment of events, and events are the fundamental components of fault tress [11]. FTA is useful to describe the root cause of an accident logically. In quantitative analysis of fault trees usually perform 2 cases [13]:

i. Fault Trees without Repeated Events

The fault tree contains independent basic events which appear only once in the structure. The probability of top event can be obtained by calculating the basic event probabilities up through the tree. For an AND Gate, the formulation to obtain the occurrence probability of top events:

$$P = \prod_{i=1}^{n} p_i \tag{1}$$

For an OR Gate, the formulation to determine the occurrence probability of top events:

$$P = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{2}$$

Where P is the occurrence probability of the top events, p_i denotes the failure probability of basic events i, and n is the number of the basic events.

ii. Fault Trees with Repeated Events

In order to obtain the probability of top event when basic events in fault tree appear more than once, then the minimal cut sets (MC) has to be determined. A MC is a collection of basic events for example $MC_i, i = 1,..., n_c$. The formula for top event if basic events appear more than once:

$$Z = MC_1 + MC_2 + ... + MC_{n_c} = \bigcup_{i=1}^{n_c} MC_i \quad (3)$$

An exact evaluation of the top event occurrence probability is:

$$P(T_Z) = P(MC_1 \cup MC_2 \cup ... \cup MC_N)$$
$$= P(MC_1) + P(MC_2) + ...P(MC_N) - (P(MC_1 \cap MC_2)$$
$$+ P(MC_1 \cap MC_3) + ...P(MC_i \cap MC_j)...)...$$
$$+ (-1)^{N-1} P(MC_1 \cap MC_2 \cap ... \cap MC_N) \quad (4)$$

III. Methodology

The research methodology is illustrated in Fig. 2. When failure happened, the first task is starting with collecting data that concerning general arrangement, equipment list, description of process and hazardous properties, the accident report, etc. Then formulate the failure mechanisms and generate the fault tree. Evaluate the probability of events using fault tree mathematical and develop the mitigation plan to reduce the failure.

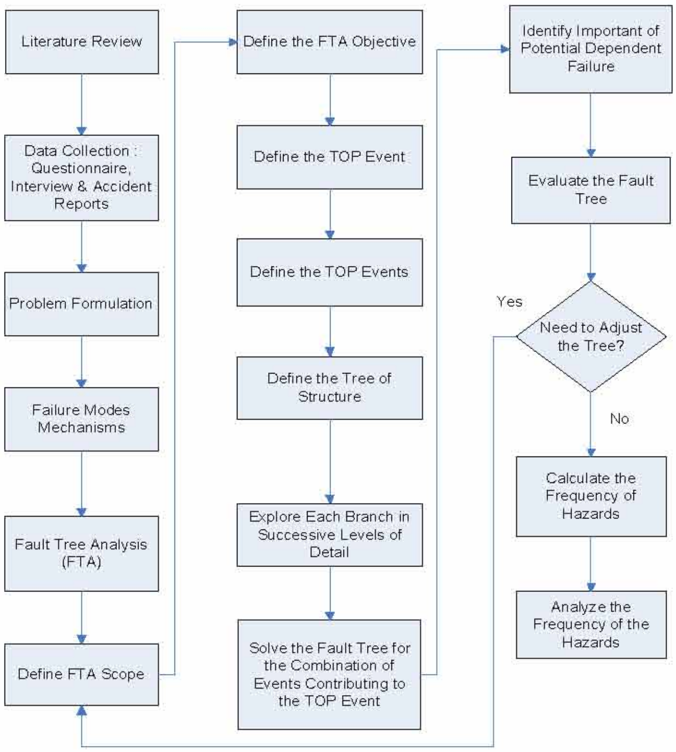

Figure 2. Fault Tree Methodology

The study flow is illustrated in Fig. 2. The first step is to gather literature review of mooring system through out the accident investigations reports, questionnaire and interview. Then those data were compiled into procedural FTA to generate the root cause of mooring system failure. Fig 3 – Fig 6 describe the fault tree (FT) diagrams.

IV. Results and Discussion

Fault tree analysis begins by determining the top event. Table IV describe the association between top event and generic fault tree. The mooring system failure is divided into mooring line break, anchor failure, anchor handling failure and appurtenance connection failure.

TABLE IV. Generic Fault Tree

Top Event	Generic Fault Tree
Mooring System Failure (MSF)	Mooring Line Breaks (MLB)
	Anchor Failure (AF)
	Mooring Winch Failure (MWF)
	Appurtenances Connection Failure (ACF)

The root cause of mooring system failure is developed based on generic fault tree.

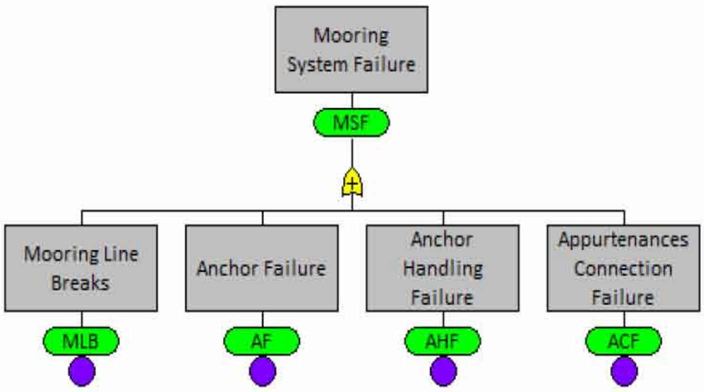

Figure 3. A FT Diagram of MSF

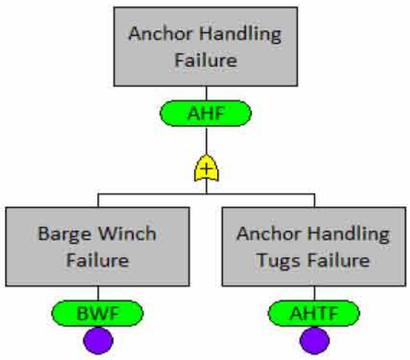

Figure 4. FT Diagram of AHF

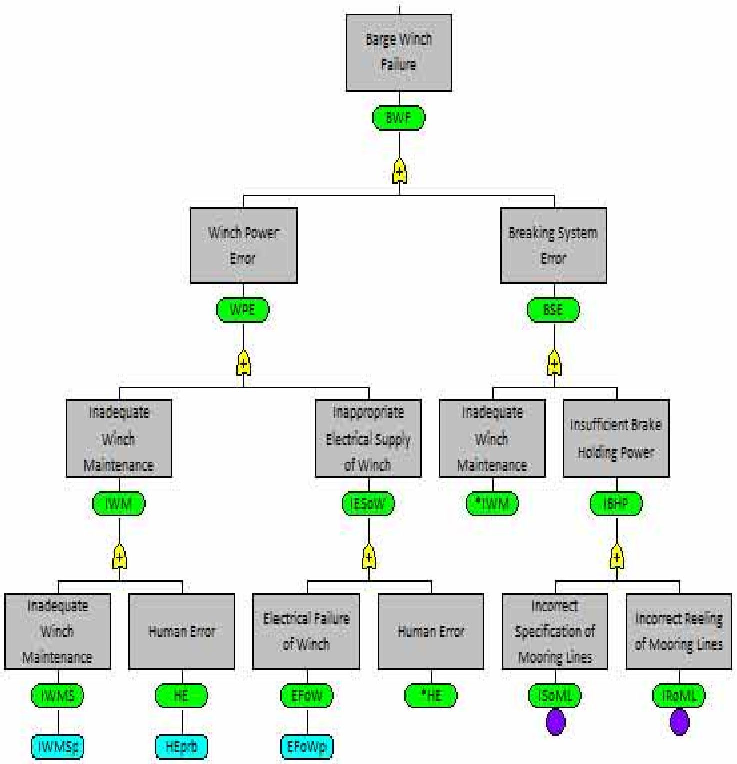

Figure 5. FT Diagram of BWF

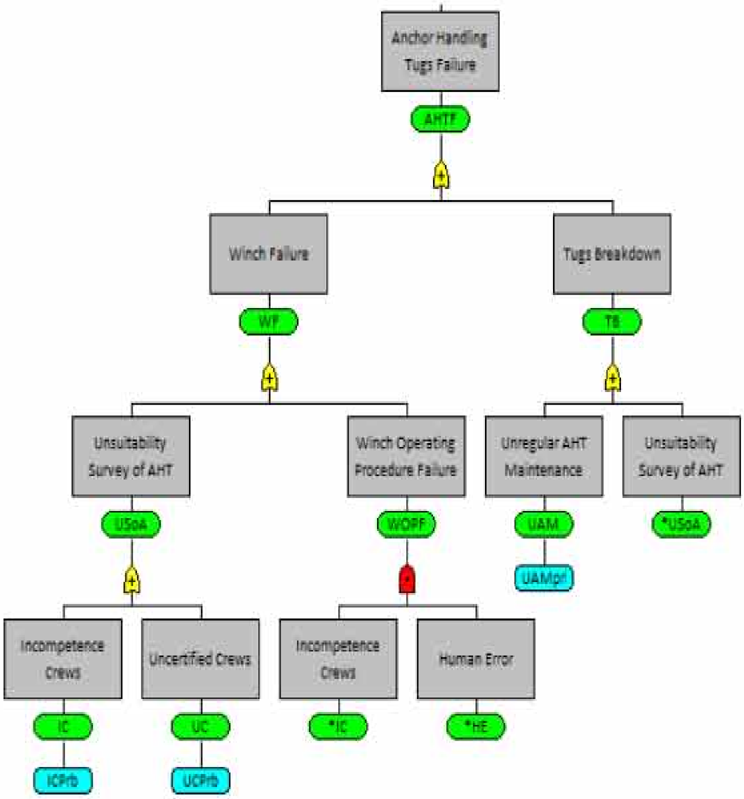

Figure 6. FT Diagram of AHTF

Fig. 3 shows the main fault tree diagram of mooring system failure (MSF). Fig. 4 shows the sub event of anchor handling failure (AHF), Fig. 5 describe the sub event barge winch failure (BWF) due to winch power error or breaking system error. In fault tree diagram, the top event is generated in order to identify the root causes of the undesired events which is called basic events. For this paper, the FT diagram of anchor handling tugs failure (AHTF) is breakdown until the basic event as shown in Fig. 6. The basic event for mooring system failure are listed in Table V. In order to investigate the possibility of failure of mooring system, the experience and knowledge of expert judgments is needed. Therefore the experts give the judgments on basic event based on frequency index developed by IMO as shown in Table I.

TABLE V. THE BASIC EVENTS OF MOORING SYSTEM FAILURE

No	Basic Events
1	Adverse Environmental Condition (AEC)
2	Debris in Seabed (DiS)
3	Design Error (DE)
4	Electrical Failure of Winch (EFoW)
5	Exposed Sharp Edges (ESE)
6	Electrical Failure (EF)
7	Excessive Waves (EWa)
8	Excessive Winds (EWi)
9	Excessive Currents (ECu)
10	Human Error (HE)
11	Incomprehensive Data Collection (IDC)
12	Improper Quality Control (IQC)
13	Inadequate Winch Maintenance Schedule (IWMS)
14	Inadequate Coating Protection (ICP)
15	Inadequate Maintenance Schedule (IMS)
16	Inappropriate Subsea Assets Inventory (ISAI)
17	Incompetence Crews (IC)
18	Manufacturing Error (ME)
19	Mechanical Failure (MF)
20	Natural Hazard (NH)
21	Poor Raw Material (PRM)
22	Rocky Seabed (RS)
23	Soft Sand (SS)
24	Uncertified Crews (UC)
25	Unregular AHT Maintenance (UAM)
26	Uncertified Equipment (UE)
27	Wrong Material (WM)

The FT evaluation uses the rules of Boolean algebra to calculate the frequency of top event. Mathematically the FT diagram of mooring system failure (MSF) can be expressed:

$$MSF = MLB \cup AF \cup AHF \cup ACF$$
$$= MLB + AF + AHF + ACF$$

The evaluation start with the calculation of cut set. Minimal cut set is the smallest combinations of basic events leading to top event occur. The cut set of the MLB, AF, AHF, ACF need to be analyzed so that the probability of top event can be found.

TABLE VI. THE CUT SET OF MLB

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3rd	0.037
2	AEC	1st	0.003
3	NH	1st	0.0023
4	HE	1st	0.0009
5	EF	1st	0.0006
6	MF	1st	0.0006
7	UC	1st	0.0004
8	IC	1st	0.0004
9	ESE	1st	0.0001
10	RS, DiS	2nd	0.0000027
Probability of MLB			0.0453027

TABLE VII. THE CUT SET OF AF

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3rd	0.037
2	AEC	1st	0.003
3	NH	1st	0.0023
4	HE	1st	0.0009
5	EF	1st	0.0006
6	MF	1st	0.0006
7	DE	1st	0.0005
8	UC	1st	0.0004
9	IC	1st	0.0004
10	IQC, PRM	2nd	0.0000015
Probability of AF			0.0457015

TABLE VIII. THE CUT SET OF AHF

Rank	Cut Set	Order	Importance Level
1	EFoW	1st	0.004
2	IWMS	1st	0.004
3	UAM	1st	0.003
4	HE	1st	0.0009
5	DE	1st	0.0005
6	IC	1st	0.0004
7	UC	1st	0.0004
Probability of AHF			0.0132

TABLE IX. THE CUT SET OF ACF

Rank	Cut Set	Order	Importance Level
1	EWa, EWi, ECu	3rd	0.037
2	AEC	1st	0.003
3	HE	1st	0.0009
4	IDC	1st	0.0007
5	IMS	1st	0.0005
6	UC	1st	0.0004
7	UE	1st	0.0004
8	IC	1st	0.0004
9	WM	1st	0.0003
10	ME	1st	0.0002
Probability of ACF			0.0438

Minimal cut set expression for the top event [14] :

$$T = C_1 + C_2 + C_3 + \ldots + C_N$$

$$T = C_{AF} + C_{MLB} + C_{ACF} + A_{AHF}$$
$$= 0.0457015 + 0.0453027 + 0.0438 + 0.0132$$
$$= 0.1480042 \text{ per year}$$

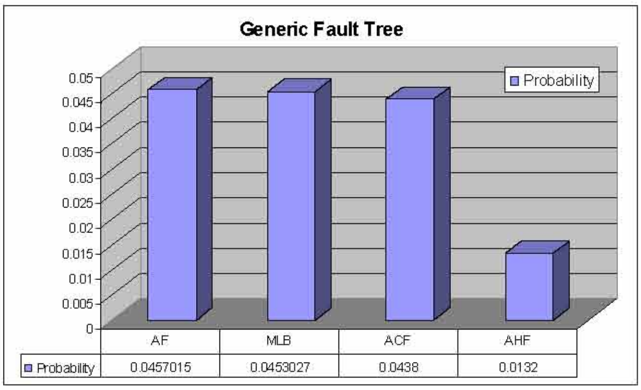

Figure 7. Generic Fault Tree Graph

From the calculation of minimal cut set it is found that the probability of top event mooring system failure is 0.1480042 per year, in terms of frequency index it is classified as reasonably probable. Fig. 7 shows the most critical event in mooring system failure is due to anchor failure (AF) with the probability 0.0457015 per year. The second critical event is mooring line break (MLB) 0.0453027 per year, followed by appurtenances connection failure (ACF) 0.0438 per year, and anchor handling failure with probability (AHF) 0.0132 per year.

V. CONCLUSION

In this paper, we obtained experts knowledge and experience on the mobile mooring system for describing possibilities of failure of mooring systems. A few key points of this paper can be highlighted as follows:

(1). FTA is a deductive method that useful to analyze the root cause of undesired events in mobile mooring systems.

(2) The main sub event failure of mooring system are mooring line break, anchor failure, anchor handling failure and appurtenance connection failure.

(3) Based on the fault tree analysis the frequency of mooring system failure is 0.1480042 per year classified as reasonably probable. By knowing the probability of failure it will be easier to do the risk maintenance and risk mitigation plans.

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