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Failure probability analysis for emergency disconnect of deepwater drilling riser using Bayesian network

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ABSTRACT

Drilling risers are the crucial connection of subsea wellhead and floating drilling vessel. Emergency Disconnect (ED) is the most important protective measure to secure the risers and wellhead under extreme conditions. This paper proposes a methodology for failure probability analysis of ED operations using Bayesian network (BN). The risk factors associated with ED operations and the potential consequences of ED failure were investigated. A systematic ED failure and consequence model was established through Fault Tree and Event Sequence Diagram (FT-ESD) analyses and then the FT-ESD model was mapped into BN. Critical root causes of ED failure were inferred by probability updating, and the most probable accident evolution paths as well as the most probable consequence evolution paths of ED failure were figured out. Moreover, the probability adaptation was performed at regular intervals to estimate the probabilities of ED failure, and the occurrence probabilities of consequences caused by ED failure. The practical application of the developed model was demonstrated through a case study. The results showed that the probability variations of ED failure and corresponding consequences depended on the states of critical basic events (BEs). Eventually, some active measures in drilling riser system design, drilling operation, ED test and operation were proposed for mitigating the probability of ED failure.

1. Introduction

With exploration and development of oil and gas resources moving into deepwater, the demand for drilling vessels capable of drilling in or beyond deepwater is increasing. When drilling operations are conducted from dynamically positioned (DP) drilling rigs, it is necessary to perform ED of the riser system from time to time to avoid serious damage to the drilling riser system and secure the well (Grønevik, 2013). The Deepwater Horizon accident, on 20 April, 2010, which might be the largest marine catastrophe, was caused partially due to the failure of the blowout preventer (BOP) and the ED system (Cai et al., 2013). ED failure, though rare, is likely to cause blowout which is the most undesired and feared accident that greatly threatens human lives, environment and assets.

Risk analysis is an effective tool to develop strategies to prevent accident and devise mitigative measures (Khakzad et al., 2013a). Quantitative risk and reliability analysis techniques have been widely used to reduce the probability of failure in offshore drilling operations. Some of these techniques include: Fault Tree (FT), Event Tree (ET), reliability block diagram, reliability graphs and the Markov chain. However, nowadays, BN is becoming a popular probabilistic inference technique for reasoning under uncertainty. The main advantage of BN is the ability to perform probability updating and sequential learning, which makes it a superior technique for risk analysis of dynamic systems (Khakzad et al., 2013a). Abimbola et al. (2015) used BN to conduct safety and risk analysis of managed pressure drilling operation. Khakzad et al. (2013a) conducted quantitative risk analysis of offshore drilling operations using Bayesian approach. Yang et al. (2017) established a systematic corrosion failure model through Bow-Tie analysis, and mapped the Bow-Tie model into a BN model to conduct failure analysis of subsea pipelines induced by corrosion. Bhandari et al. (2015) conducted a dynamic safety analysis of deepwater managed pressure drilling and underbalanced drilling operations using the BN. Cai et al. (2012a, 2012b, 2013) utilized BN to conduct quantitative risk assessment of subsea BOP operations and reliability evaluation for subsea BOP control system. A BN-based failure evolution model for subsea pipelines was developed by Li et al. (2016).

Some hazards related to uncertainty are difficult to model by traditional QRA approaches. Furthermore, historical records of some risk scenarios, particularly extreme hazardous events, are often incomplete

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and insufficient. Therefore, it may be necessary to carry out a risk assessment based on multiple hazards which are represented in various forms such as probabilistic data, experts' opinions and linguistic representations. The fuzzy set theory can be used to present subjective, vague, linguistic and imprecise data and information effectively. In the Fuzzy Fault Tree Analysis (FFTA), the probability values of components will be characterized by fuzzy numbers. Using fuzzy set theory, fuzzy number in linguistic term can be transformed into fuzzy failure probability of BEs, and quantitative risk analysis of top events can be conducted by FT method. Lavasani et al. (2011, 2015a, 2015b) applied fuzzy set theory to evaluate the risk of leakage in abandoned oil and natural-gas wells and Deethanizer failure in petrochemical plant operations. Ren et al. (2009) developed an offshore risk analysis method using a fuzzy BN where triangular fuzzy membership functions were used to elicit expert judgments. Ferdous et al. (2009) proposed a methodology for computer aided FFTA. Chen et al. (2014) conducted risk assessment of an oxygen-enhanced combustor using a structural model based on the Failure Mode and Effects Analysis (FMEA) and FFTA. Shi et al. (2014) performed FFTA for fire and explosion accidents for steel oil storage tanks.

In practical operational conditions, various factors, e.g. human, design, operation, time, equipment and control are all able to cause the failure of ED which could cause disastrous consequences in deepwater drilling. However, studies for ED operations of deepwater drilling riser from risk perspective can only be found sporadically in literature. Thus, it is necessary to conduct a comprehensive study to address the failure probability analysis of ED operations for the actual engineering requirements.

The objective of this paper is to propose a failure probability analysis methodology for ED operations of deepwater drilling risers, which could be used to assess the probabilities of ED failure and different failure consequences. In this research, a FT-ESD model was developed to present a systematic accident scenario and accident evolution process caused by ED failure. A BN model was mapped from the developed FT-ESD model to identify the critical events, analyze the most probable paths for ED failure and the most probable paths of the consequences resulting from ED failure by updating the prior probability of BEs. The BN model also aimed to investigate the failure probability of ED by introducing new critical BEs. Finally, some suggestions and measures for ED operations are proposed to reduce the probability of failure accident.

The paper is structured as follows: Section 2 introduces the process, analyzes the reasons of ED, and investigates the mechanism of factors influencing the ED operations. In Section 3, the failure probability analysis methodology for ED operations of deepwater drilling riser is proposed. Section 4 identifies the hazards and analyzes the accident evolution process of ED failure by FT and ESD. Section 5 is a case study regarding the application of BN in quantitative failure probability analysis of deepwater drilling riser ED operations. Finally, the conclusions are presented in Section 6.

2. Background

2.1. Deepwater drilling riser system

Deepwater drilling conductor is the first layer of casing installed during the well construction in deepwater drilling, which is generally jetted into the formation without well cementing. After jetting the conductor with low pressure wellhead (LPW), completing the installation of the casing surface tubular with high pressure wellhead (HPW) and cementing, drilling operation is followed by deployment of riser system and LMRP/BOP by making up the riser joints.

The main components of the riser column include BOP/LMRP stack, lower flex joint (LFJ), slick and buoyancy riser joints, telescopic joint (TJ) and upper flex joint (UFJ). The top end of the riser column is connected to the drilling vessel through the tension system. The TJ consists of inner and outer barrels where the relative motion (stroke) of these barrels can compensate for the length variations of riser column with the motion of the drilling vessel. The LFJ and UFJ can improve the mechanical performance for both ends of the riser column to avoid excessive bending moment and hence damage to the risers (Chang, 2008).

The subsea BOP/LMRP stack includes LMRP and BOP, which is usually equipped with two hydraulic connectors, namely, the LMRP connector and wellhead connector. The LMRP connector is located in the middle of two annular preventers, which is used to connect the LMRP to the BOP, and the wellhead connector is used to connect BOP and HPW (Cai et al., 2012a, 2012b). If ED is activated automatically or manually under extreme conditions, the LMRP will disconnect from BOP at the LMRP connector, and the riser column will be lifted up and suspended by the tensioners eventually after the disconnect is completed. If there is drill pipe in the drilling riser, the blind shear rams in BOP will cut through the pipe and seal the well before disconnect.

2.2. Reasons for emergency disconnect

Generally, There are four reasons for the ED of the drilling riser system that include drift-off, drive-off, storms and internal solitary waves.

2.2.1. Drift-off

Drift-off is an event normally caused by loss of power, malfunction in the power system, engine breakdown, or mechanical and human errors. When the DP system can no longer hold the position, the increasing offset of the drilling vessel due to wind, wave and current will cause large horizontal force and bending moment to the subsea wellhead by drilling riser system, and the ED must be activated to avoid possible accident. If the ED operations can't be completed successfully in 60 s at most, it may damage the wellhead or break the riser joints. Once the integrity of the well is damaged, the blowout accident will occur inevitably. According to the existing literature, it has been stated that the occurrence probability of drift-off event is 2×10^{-3} per year (Olsen, 2001).

Establishing alert offsets for the ED of the vessel-connected riser system through drift-off analysis is used to determine the point of disconnect. Generally, the alert offsets settings are as follows: green region-drilling normally; yellow region-stop drilling and make the preparation for ED while the riser is in the “connected non-drilling mode”; red region-the ED is initiated automatically (it can also be initiated manually in advance) and must be completed before reaching the blue region; blue region-the suspended riser column is in survival mode (Ju et al., 2012).

2.2.2. Drive-off

A drive-off is much the same as a drift-off, but it comes from a malfunction in the DP system causing the rig to drive off from its location. This is a very critical event due to the higher velocity of the vessel, and it provides a short available time to activate the ED before the horizontal offset gets too large. The occurrence probability of drive-off event is 1.6×10^{-5} per DP hour (Ambrose et al., 2001a, 2001b).

2.2.3. Storm

Generally, the MODU will disconnect from the BOP before a storm is fully developed which is called “planned disconnect”. However, if the storm is larger than predicted or if an anticipated rapidly-developing seastate happens, an unplanned ED would be needed to secure the drilling risers and wellhead.

2.2.4. Internal solitary waves

Internal solitary waves are the nonlinear large amplitude waves existing in the oceanic pycnocline (Cai et al., 2012a, 2012b). A large number of measurements and remote-sensing observations have shown