Safety assessment in oil drilling work system based on empirical study and Analytic Network Process

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ABSTRACT

Safety assessment is an essential work to guarantee the safety of oil drilling. There are relations and dependencies between human factors in oil drilling work system. Therefore, the safety of oil drilling work system should be analyzed in a comprehensive way. The Human Factors Analysis and Classification System (HFACS) is applied to establish rational and applicable index system for investigating human errors. The Analytic Network Process (ANP) method is used to obtain the priorities of human factors considering the interdependences, however, the deficiency of ANP is that the obtained results are subject to experts' cognitive limitations and psychological biases. The Structural Equation Modelling (SEM) is used to form the ANP model auxiliary, which may be expected to overcome subjective opinions from experts and provide a more pertinent and practical safety strategies. A survey is conducted to explore the importance of human factors through questionnaires of which 283 pieces made up the original data. Afterwards, the human factors' weights are calculated by the ANP method. As a comparison, a frequency-based method is also used to obtain the frequencies of factors and observations causing accidents using accident reports. The causal chain and the priorities of the importance of human factors are explored by this hybrid method; the results are consistent with the experience and knowledge of safety management. We discuss the interdependencies between the human factors and the priorities in general, whilst, the specific safety requirements and recommendations in the hoisting and lifting system are also provided as an example.

1. Introduction

In recent years, safety problems in oil drilling have obtained many concerns. As the drilling industry involves complex and hazardous activities, it is of great importance to assess attendant risks in which human factors make up a large proportion. The hoisting and lifting systems are one of the most important components in oil drilling industry; measures should be taken to lower the risk of human factors (Zhou et al., 2017).

Many safety studies have been done in drilling industry. Amir-Heidari et al. (2015) carried out a case study to assess the human factors, which are identified by what-if and structured brainstorming. Zhao et al. (2011) assessed the qualification of human factor risks associated with the drilling process based on Delphi method. Strand and Lundteigen (2016) studied classification of the human factors and put forward a relative importance of assessment criteria in each risk influencing factor. Abimbola et al. (2015) analyzed the shortcomings existing in overbalanced and underbalanced drilling technique, and proposed a Bayesian network model for managed pressure drilling risk

assessment. Ataallahi and Shadizadeh (2015) studied the blowout in onshore Iranian drilling industry, and provided fuzzy method to develop the consequence of blowout for Iranian onshore drilling industry. Ramzali et al. (2015) carried out a survey on a leakage event in production phase, and assessed the barriers of the initiating event by using Event Tree Analysis. Pranesh et al. (2017) analyzed the case study of deep water horizon offshore oil platform accident, in which failures in oil and gas cementing operation exists, and concluded that this tragedy is due to complete human errors and employee's poor leadership abilities. Researchers studied human factors from different views of classification, while the hierarchical and interactional study of human factors in drilling industry is still incomplete; moreover, there are rare studies in the safety assessment considering the interdependences between human factors in the hoisting and lifting system in oil drilling industry.

It has been acknowledged that accident analysis must rely on systemic and organizational models (Rasmussen, 1997; Reason, 1997). And it is essential to choose a model before starting the investigations, according to the characteristics of the system and the nature of the

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accident (Chauvin et al., 2013). Human Factors Analysis and Classification System (HFACS) is a generic human error framework originally developed for US military aviation as a tool for the analysis of the human factors aspects of accidents. The HFACS is perhaps the most widely used human factors accident analysis framework, including shipping accidents (Akyuz, 2017), mining (Patterson and Shappell, 2010), and construction (Garrett and Teizer, 2009). Wiegmann and Shappell (2001) suggested that the HFACS framework bridges the gap between theory and practice by providing safety professionals with a theoretically based tool for identifying and classifying human errors. In HFACS, factors in higher level affect factors in lower levels.

Although HFACS can provide a good capture of the complexity of the human factors systems, it cannot provide the safety-related priority of human factors. Many organizations adopt approaches such as safety checklists, Fault Tree Analysis (FTA) and Likelihood Exposure Consequence (LEC), which are built on a qualitative or semi-qualitative basis. Chen and Yang (2004) stated that the above mentioned methods cannot be used to assess the current status of safety management and the risk level of high risk operations in a quantitative way. The Analytic Hierarchy Process (AHP) method is a quantitative analysis method, which can mathematically model the decision process without much information, and it can provide a convenient way for multi-objective, multi-criteria, unstructured decision problems. The Analytic Network Process (ANP) is an extended form of the AHP. Although both the AHP and the ANP derive ratio scale priorities by making paired comparisons of elements on a criterion, differences exist between them. First, although the AHP is a special form of the ANP, the ANP can handle interdependences within a cluster (inner dependence) and among different clusters (outer dependence). The ANP method reserves the core conception of the AHP method, which divides the decision system into hierarchical structure, and believes that the criterions within lower level are dominated by the criterions of adjacent higher level. Second, the HFACS divides human factors into four levels (Li et al., 2008; Madigan et al., 2016). Human factors in the higher level affect factors in the adjacent lower level, thus they can be clustered by the hierarchical HFACS framework, which tightly aligned with the ANP method (Zhan et al., 2017). Third, the ANP is a nonlinear structure, while the AHP is hierarchical and linear, with a goal at the top level and the alternatives on the bottom level (Liou et al., 2011).

On the account of inter-dependencies among the human factors in oil and gas drilling operations, it could prioritize among different influences by using the ANP method. ANP method has already been applied in safety assessment areas by many researchers. For instance, Jin et al. (2014) designed an assessment system for secondary task driving safety by using ANP. Dağdeviren et al. (2008) employed the ANP to determine the weights of factors and sub-factors necessary to calculate the faulty behavior risks. Zhan et al. (2017) combined the ANP method with fuzzy decision making trail and assessment method to find out leading casual factors in railway accidents.

Although ANP is a powerful method in safety assessment areas, it has some limitations. In the ANP, the most important work is to establish the reciprocal pairwise comparison matrixes. Comparisons between the two given alternatives are carried out using experts' judgments, feelings, experience, and intuition (Saaty and Vargas, 2012). As ANP heavily relies on expert judgment, the results obtained are subject to experts' cognitive limitations and psychological biases. Experts might be inherently optimistic in some cases, inherently pessimistic in other cases, or inherently overconfident in still other cases (McKay and Meyer, 2000). Such cognitive limitations can produce biased results; thereby guide the conclusions of the analyses into a sub-optimal precaution.

It is suggested that statistical methods should be used to generate more accurately dependent relationship among factors (Metin et al., 2008). Structural Equation Modelling (SEM) is a family of statistical techniques used to specify, estimate, and test hypothesized theoretical relationships among variables that are organized and connected in

substantively meaningful models (Fan and Wang, 1998). SEM developed by Jöreskog and Yang (1996) is a comprehensive statistical technique which is used to test casual relationships between observed and latent variables (Yuluğkural et al., 2013), which is one of the most popular research methods in the social sciences. Tomas et al. (1999) established a structural equation model of accidents and discussed the safety variables in the model. Krajangsri and Pongpeng (2016) used SEM to inform how sustainable infrastructure assessments affect construction project success and provided a guideline for developing sustainable infrastructure projects. Zhang et al. (2016) used SEM to examine the interactions between the contributory factors of coal mine accidents.

We integrate SEM with ANP to reduce experts' subjective biases. More specially, we use the relationship between the human factors obtained from SEM to form the structure of the ANP model, and use regression coefficients obtained from SEM to establish reciprocal pairwise comparison matrixes (Dangol et al., 2015). However, there are some important differences between the study of Dangol et al. and ours. First, the application of ANP in their study serves for the formation of SEM to search the relationship between factors, while, in our study, the application of SEM serves for the formation of ANP to conduct safety assessment. Second, the factors in our study are more complex and hierarchical than theirs, thus we divide the human factors in the four levels into 13 separate SEM diagrams, which not only coincides with the interdependences between the factors, but also simplifies the test and modification during the modelling process.

In all, we hope to establish a more precise research method to reduce the errors, which may be caused by subjective judgment. At last, to analyze the causes of an accident and confirm the results of this empirical method, case statistical analysis using the frequency-based method is carried out to compare with it. We also conduct the safety assessment in hoisting and lifting system as an example.

The rest of this paper is organized as follows: In Section 2, the methodology of this empirical method is proposed and the basic concepts of empirical study and ANP are reviewed. In Section 3, the implementation using the proposed method is presented on the case study of hoisting and lifting system; also the results of frequency-based method are given. Based on the results of two different methods, discussion and recommendations are given aiming at the safety improvement of activities on hoisting and lifting system. Section 4 gives a review and conclusion of the whole work.

2. Methodology

The aim of this study is to evaluate the importance of human factors by the hybrid method of ANP and SEM and provide safety recommendations in oil drilling work systems. Empirical study based on SEM and questionnaires could collect a lot of expert advices. We applied the SEM model to construct the ANP model, which can reduce the biases of experts in ANP evaluation. This research was divided into six phases illustrated in Fig. 1. Human error taxonomy based on HFACS frameworks is used to establish index system. Based on the index system, questionnaires are carried out to get the empirical data, which acts as the import to the SEM method. The structure of the SEM can be built according to the HFACS framework; the regression coefficients obtained from SEM can be used to build the pairwise comparisons in the ANP method. Correspondingly, the structure of ANP also can be built according to the relationship of variables in SEM. The weight of each human factor can be obtained from the results of ANP. Furthermore, we can compare the results of frequency-based methods with the results of the SEM-ANP method and verify the validity of the latter method. At last, the results given by the empirical study and ANP are also useful to provide practical recommendations on improving the safety goal in drilling industry.
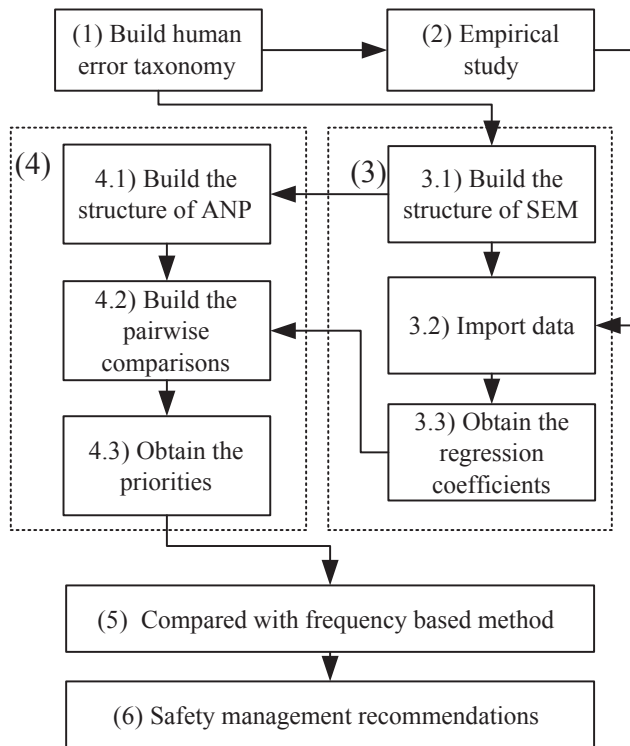
Fig. 1. The technical route of the empirical study and Analytic Network Process.

2.1. HFACS

Establishing a rational and comprehensive index system is the key of safety assessment; therefore, we applied the HFACS to build a safety assessment index system. Fig. 2 shows an overview of the HFACS framework. The HFACS framework includes four main levels of investigation schema: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences.

The descriptions for categories and sub-categories of the HFACS are different in various areas (Patterson and Shappell, 2010; Chauvin et al., 2013; Zhan et al., 2017). Unfortunately, in the field we are approaching

there is no universally agreed classification system, hence the taxonomy we adopt must be made for our specific purpose. While using the HFACS framework, we considered the characteristics of oil drilling accidents to adjust the model, in combination with abovementioned reference works and oil drilling safety standards established by the state (NEA, 2014), as well as actual oil drilling accidents, to reselect some of the index factors, and ensure that each factor in the framework has a certain generality and independence simultaneously. The definitions and detailed descriptions for each category of the HFACS combined with the characteristics of drilling industry are given in Table 1.

A survey based on the HFACS was developed to investigate the opinions of safety managers, safety supervisors and operators about the importance of human factors in oil drilling industry. The questionnaires were the main form of this survey, and were evaluated using a three-point Likert scale ranging from 1 (not very) to 3 (very). Questions are corresponding to the categories and sub-categories, and are divided into the cost and effectiveness indicators, such as inadequate supervision, operators in good physical condition, etc.

2.2. Structural equation modelling

SEM involves the assessment of the two models: (1) a measurement model, and (2) a structural model. The model called the measurement model analyses how much the latent variables are represented by observed variables and defined as confirmatory factor analysis. The second model is the structural component, which is a regression method consisting of latent variables and it examines casual relationships between latent variables (Jöreskog and Sörbom, 1993). Fig. 3 is a generic SEM schematic diagram used to illustrate the basic concepts in SEM.

In Fig. 3, X and Y represent measured variables, η represents endogenous latent variable, ξ represents exogenous latent variable; γ is the coefficient between endogenous latent variable and exogenous variable, δ and ε are the residual errors. Because in the HFACS framework, factors in sub-categories are performances of factors in the main categories, the factors in a main category can be described as latent variables while the factors of sub-categories can be described as measured variables. Similarly, the questions in questionnaires are the descriptions and reflections of the factors performances in sub-categories. Thus, factors in sub-categories can be described as latent variables while the questions can be described as measured variables.
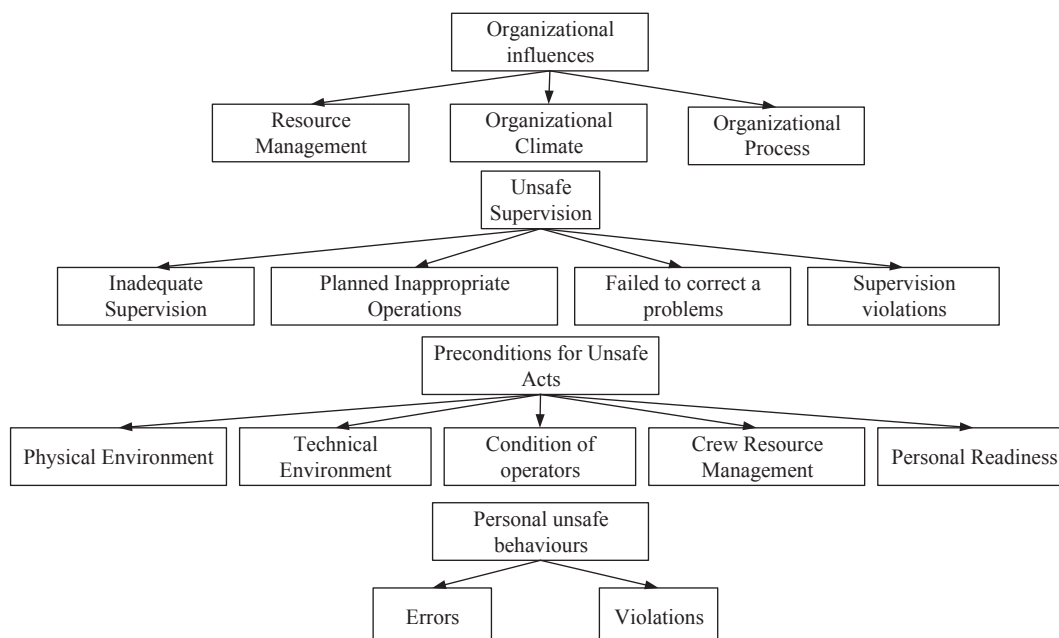

Fig. 2. Human factors analysis and classification system framework.

Table 1
Brief descriptions for categories and sub-categories of the HFACS.

Main categories	Sub categories	Description
Organizational influences (OI)	Resources management (RM)	The allocation of human resources, capital and facilities, like safety belt, safety goggles, life jacket and etc.
	Organizational climate (OC)	The safety climate, faith of safety and recognition of safety
	Organizational process (OP)	Formal process by which the vision of an organization is carried out including operations, procedures, and oversight among others, including safety production laws, regulations and other standard; incentivization; clearly defined safety objectives; risk management programs
Unsafe supervisions (US)	Inadequate supervision (IS)	Negligence of duty, fail to provide guidance of equipment maintenance, fail to provide skill and safety training and training track qualifications, fail to check the qualification of equipment; safety troubleshooting program with a clear investigation of the purpose, scope, methods and requirements; safety oversight (including all production and business related sites, environment, personnel, equipment, facilities and activities) and methods; hazard identification and safety evaluation for dangerous facilities or sites; register and archive for identified major hazards in time; taking measures to monitor major hazards; identification and appropriate control measures of potential equipment failure and error operation; fail to provide planned control on change of institution, personnel, process, technology, equipment, operating process and environment that is permanent or temporary change
	Planned inappropriate operations (PO)	Inappropriate plan to the actual conditions, such as substandard maintenance plan and dispatching plan, etc. Fail to provide correct information and data, maintenance and drilling mission not in accordance with regulations
	Failed to correct problems (FP)	Failed to identify existing equipment failure and errors operation, fail to initiate corrective action
	Supervision violations (SV)	The willful disregard for existing rules, regulations, instructions, or standard operating procedures by management during the course of their duties
Preconditions for unsafe acts (PA)	Physical environment (PE)	The operational setting (e.g., weather, altitude, terrain) and the ambient environment, such as heat, vibration, lighting and toxins. For example, confined space, high places, hoisting and etc.
	Technological environment (TE)	Safety warning signs and safety colors complying with the requirements on equipment or workplace; safety protection measures; safety equipment and safety facilities; safety technical disclosure; the drilling safety technology solutions; Performance and maintenance; temporary power in accordance with the provisions to drilling safety; the design of equipment and controls, display/interface characteristics, checklist layouts, task factors and automation; Material certificate and material testing; control material production, transport and stacking
	Condition of operators (CO)	Operation requirements beyond the scope of personal ability, attention-deficit, mental fatigue, self-satisfied, haste, misplaced motivation, and etc. Pathological conditions such as medical illness, physical trauma, physical fatigue for individuals
	Crew resource management (CM)	Inappropriate assignment of team members, insufficient number of team members, lack of team leader and poor teamwork; poor communication between crew; teamwork issues (including pre-shift meeting; predicting dangerous activities) that impact performance
	Personal readiness (PR)	Violations of staff rest requirement and alcohol inspection, excessive physical training before work, lack of experience, poor training result, and lack of safety awareness, etc.
Unsafe acts of operators (UO)	Errors (E)	Misdiagnosed emergency and wrong response to emergency, wrong plan due to exceeding ability, improper operation and maintenance procedure, poor decision, and etc.; wrong operations, omitted step in procedure, poor technique; errors caused by improper cognitions
	Violations (V)	Operation and maintenance not in accordance with the standards, not qualified for mission, fail to properly prepare for work, speeding, and etc.

The structure model in Fig. 3 can be expressed by matrix equation (1):

$$\eta = \Gamma\xi + \zeta \qquad (1)$$

where Γ is a $m \times n$ matrix, representing the regression coefficient from ξ to η; ζ is the deviation of endogenous latent variable. Each single-headed arrow in the model represents a regression weight, indicating the influence of the variable where the arrow originated on the variable receiving the arrow (Merchant et al., 2013). The regression coefficient can also give a look at the relative importance of measured variables in each latent variable. Furthermore, the regression coefficients also represent the relationship of variables; the higher value
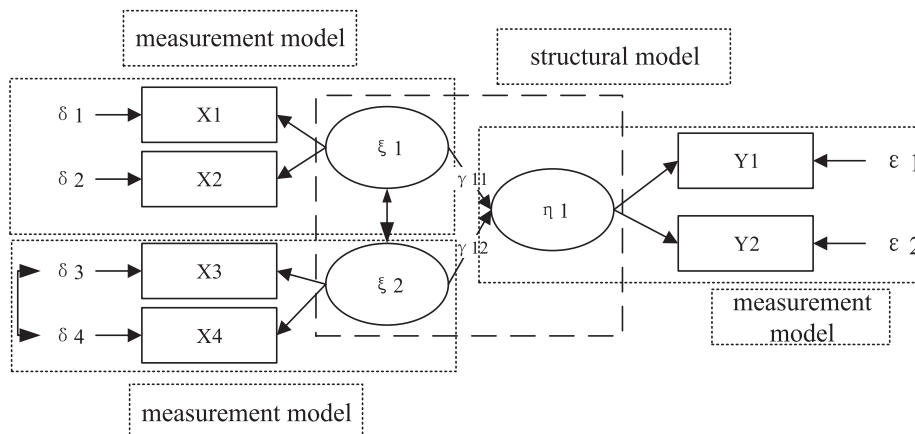

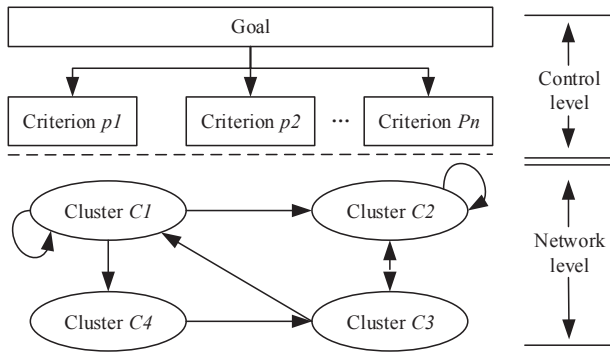**Fig. 3.** A generic SEM schematic diagram.

Fig. 4. A Framework of ANP.

means the closer relationship (Liang et al., 2012).

Although SEM can be employed efficiently to test a theorized relationship, its effect is limited for safety analysts because it does not help to achieve the ultimate goal of safety assessment, which is to prescribe safety recommendations. SEM cannot be used to prioritize human factors or to choose those that will create the most value for safety analysts. Our developed hybrid model overcomes such limitations by using the ANP method in conjunction with SEM.

2.3. ANP method

ANP allows for the consideration of inter-dependencies among and between the levels of attributes and alternatives (Partovi, 2001). As shown in Fig. 4, a network structure of ANP consists of control level and network level, including at least one goal, criteria and clusters. The main components of the ANP model can be thought to correspond to latent variables in the SEM model and the subcomponents correspond to observed variables (Yuluğkural et al., 2013).

In network level, a network spreads out in all directions and involves arrows between clusters or loops within the same cluster. These arrows and loops indicate the relations among clusters or within a cluster. For example, a single arrow from cluster C1 to cluster C2 means that cluster C1 impacts cluster C2. A two-way arrow between cluster C2 and C3 indicates that cluster C2 and cluster C3 influence each other. A loop in cluster C2 implies that there are interactions among elements within cluster C2.

Suppose there are n clusters, denoted by $C_1, C_2, …, C_n$, and each cluster C_i has n_i elements, $e_{i1}, e_{i2}, …, e_{in_i}(i = 1,2,...,n)$. To determine weights of all elements in clusters $C_i(i = 1,2...,n)$ by ANP, the following procedure needs to be performed:

(1) Construct the network structure based on interactions among criteria and sub-criteria
(2) Determine the weighting matrix **A**

Considering interactions and feedback among clusters or within clusters, judgment matrices $A^i = (a_{kj}^i)_{n×n}$ $(i = 1,2,...,n)$ are constructed by pairwise comparisons with the 1–9 scale, where a_{kj}^i indicates that an influence degree of cluster C_k on cluster C_i is a_{kj}^i time as important as that of cluster C_j on C_i. If A_i is completely consistent or of acceptable consistency, the priority vector of matrix A_i, denoted by $w_i = (w_{i1}, w_{i2},...,w_{in})^T$, can be computed by the eigen-value. Otherwise, A_i should be modified. If cluster C_i is independent of C_j, then $w_{ij} = 0$. Thus, the weighting matrix $A = (w_1, w_2,...,w_n)$ can be determined and simply denoted by $A = (a_{ij})_{n×n}$.

(3) Construct the supermatrix W

The supermatrix **W** is composed of many submatrices W_{ij} $(i,j = 1,2,···,n)$ as Eq. (2):

$$W = \begin{array}{c} \\ C_1 e_{11}, L \ e_{1n_1} \\ C_2 e_{21}, L \ e_{1n_2} \\ L \\ C_n e_{n1}, L \ e_{nn_n} \end{array} \begin{pmatrix} W_{11} & W_{12} & L & W_{1n} \\ W_{21} & W_{22} & L & W_{2n} \\ L & L & L & L \\ W_{n1} & W_{n2} & L & W_{nn} \end{pmatrix} \qquad (2)$$

In submatrix W_{ij}, the kth column vector is a local priority vector representing influence degrees of all elements in cluster C_i on the element e_{jk} in cluster C_j. Therefore, the sum of elements in kth column of W_{ij} should be equal to 1. This property also holds for other columns of W_{ij}. The process of determining matrix W_{ij} is similar to that of determining matrix **A**. Additionally, if the ith cluster has no influence on the jth cluster, then $W_{ij} = 0$. For instance, it can be seen from Fig. 4 that $W_{21} = 0$, but $W_{12} ≠ 0$. The supermatrix provides relative importance of all components and Compute the weighted supermatrix

(4) Compute the weighted supermatrix $\overline{W}$

By multiplying supermatrix **W** with matrix **A**, the weighted supermatrix can be derived as $\overline{W} = (\overline{W}_{ij})_{n×n} = A × W$, where $\overline{W}_{ij} = a_{ij} × W_{ij}$ $(i,j = 1,2,...,n)$.

(5) Determine the limit matrix $W^∞$

The limit matrix can be calculated as $W^∞ = \lim_{k→∞}\overline{W}^k$. In this limit matrix, all components in each row are the same. In the limit matrix, the constant values of each value are determined by taking the necessary limit of the weighted supermatrix.

(6) Determine overall weights of elements with respect to the goal

Since each cluster C_i has n_i elements, there are $\sum_{i=1}^n n_i$ elements in the ANP model. The limit matrix $W^∞$ is a $t × t$ matrix, where $t = \sum_{i=1}^n n_i$. The overall weight vector of elements with respect to the goal, denoted by $ω = (ω_1, ω_2,...,ω_t)^T$, can be determined from the limit matrix $W^∞$, where $ω_k$ is the element of the kth row of matrix $W^∞$.

2.4. Combination of SEM and ANP

As the main components of the ANP model could correspond to latent variables in the SEM model and the subcomponents correspond to the observed variables, the structure of the ANP can be formed according to the relationships between human factors in SEM. Furthermore, the regression coefficients obtained from SEM can be used to get the pairwise comparisons in the ANP. For example, in Fig. 3, if the correlation ($γ11$) between $η1$ and $ξ1$ is significantly higher than the correlation ($γ12$) between $η1$ and $ξ2$ with the prohibitive subscale, then we consider $ξ1$ to be more important than $ξ2$. Based on the relative importance obtained by the SEM method, pairwise comparisons for all combinations can use the fundamental comparison scale of the ANP, which ranges from 1 to 9 (Dangol et al., 2015). We assigned a value of "1" when two independent variables equally influence dependent variables. Similarly, we assigned a value of "7", when we expect a given independent variable to strongly influence a dependent variable compared to the second independent variable. To be conservative, the value of 9 is abnegated. After the comparison matrices are completed, the comparison matrix, supermatrix, weighted supermatrix and limit matrix can be calculated successively. According to the limit matrix, the weight of each factor can be obtained. Factors with higher weights have higher priorities. In conclusion, we combined the ANP with the SEM model. By using SEM model, the experience biases generated by experts could be reduced.

2.5. Frequency-based method

To demonstrate the benefits of this hybrid method, the frequency-based method is also used to calculate the frequencies of the accident causes in accident reposts and acts as a comparison. Frequency-based method could provide a general look of accident reports directly and clearly. Furthermore, as the sample size is expanded, the results obtained by the frequency-based method will become more consistent with the truth. The procedure can be described as follows.

Step 1: Collect, decompose and record accident reports in the oil drilling industry into a database.

In the decomposing process, to get the more detailed human factors, the listed unified descriptions of human factors called *observations* are defined to bridge the gap between the accident causes and these factors. For example, to the "Personal readiness", the observations are (1) safety awareness; (2) lack the experiences of dealing with sticking, etc.

Step 2: A human factor/observation will be marked as "1" if it causes an accident and marked as "0" if it is on the contrary.
Step 3: Calculate the frequencies of human factors and observations causing accidents.
Step 4: Normalize the values and get the weight of each factor.

3. Results and discussion

3.1. Questionnaires

Copies of the draft questionnaire that applied HFACS and other standardized documents or results were sent to several industry professionals to test the validity. After incorporating the professionals' insights, the final version of the survey questionnaire was used to assess how important each of the factors is for safety production. As an example, the questions used to describe "Organizational process" can be: the necessity of establishing and perfecting the safe production responsibility system; the necessity of work procedures to protect the drilling safety; etc. In the questionnaire, assessment was measured using three-point Likert scale ranging from 1 (not very) to 3 (very). The assessment was scored on a scale from 1 to 3 (1 = VI (very important/necessary); 2 = GI (generally important/necessary); 3 = NVI (not very important/necessary)). We formed a questionnaire with 49 detailed items, which include 11 items about organizational influences, 16 items about unsafe supervision, 14 items about preconditions for unsafe acts, and 8 items about unsafe acts of operators. The questionnaires were issued in 418 pieces; 283 valid pieces were collected.

3.2. Reliability analysis and validity analysis

On the account of the existence of invalid data, the quality of the survey needs to be analyzed. We adopt the IBM SPSS Statics 22 software to wipe off questionnaires which are insignificance, such as questionnaires containing lots of blanks and repetitions. The reliability and validity of the data are the two indicators measuring the quality of the data. SPSS 22 software also provide "reliability and validity analysis" function, the result is shown in Table 2.

Cronbach's alpha coefficient is the internal consistency coefficient, which is one of the most commonly used indicators to test questionnaire's reliability, reflecting the consistency and stability degree of the scale items. The Cronbach's alpha coefficient needs to reach 0.9, and the closer to 1, the reliability of data is higher. In Table 2, the Cronbach's alpha coefficient of this survey reaches 0.906, indicating good data reliability.

KOM and Bartlett's test are widely used to examine the validity of data. KMO is the sampling appropriate parameter, when the value is greater than 0.5, meaning that these variables could be conducted

Table 2
The result of reliability and validity analysis.

Latent variables	Number of measured variables	KMO	Bartlett's test			Cronbach's Alpha
			Approx. Chi-Square	df	sig	
Organizational Influence	3	0.639	209.08	3	0.00	0.722
Unsafe Supervision	4	0.757	314.919	6	0.00	0.767
Preconditions for Unsafe Acts	5	0.858	652.665	10	0.00	0.853
Unsafe acts of operators	2	0.500	230.689	1	0.00	0.839
Safety goal	14	0.914	2317.017	91	0.00	0.906

further analysis. Bartlett's test, also called Bartlett test of sphericity, if the variable correlation coefficient matrix is a unit, each independent variable factor analysis method is invalid. If the test results show that the Sig. < 0.05, the correlation between variables and factor analysis are effective. According to Table 2, the entire questionnaire data's KMO value is 0.914 and the values of Sig. are 0, which shows good questionnaire construction validity. In short, the reliability and validity of the survey data are desirable.

3.3. Regression coefficients by SEM

There are 13 SEM models in total to obtain the correlations of factors in main categories and sub-categories from the standardized regression weights in each model.

One of the models is to show the relationships of factors in the main categories. "Organizational influences", "unsafe supervisions", "preconditions for unsafe acts", and "unsafe acts of operators" are both human categories that affect "safety goal". Furthermore, each category is characterized by several factors. For example, "organizational influence" is considered to be a three dimensional construct composed of "resource management", "organizational climate" and "organizational process". The SEM to obtain regression coefficients could be a second order construct. According to the design requirement of the second order SEM, "organizational influence", "unsafe supervision", "preconditions of unsafe acts", and "unsafe acts of operators" are endogenous latent variables in the first order construct. "Safety goal" is the exogenous latent variable in the second order construct. Because of the variables in the first order construct are considered to be endogenous latent variables, each variable need to add the estimated residual item. In the initial second order model, assumed that there is no errors covariance and cross-loading, each measured variable is affected by one variable in the first order construct. The structure is shown in Fig. 5.

It is tedious and difficult to calculate and optimize the relationships of all factors in one SEM model; therefore, we decomposed the complex model into 12 relative easier models according to the characters that factors in the higher level only affect factors in the adjacent lower level. These models represent the relationships of sub-categories, for example, "organizational process" affects "inadequate supervision", "planned inappropriate operations", "failed to correct known problems" and "supervisory violations". The factor in the higher level, "organizational process", is considered to be the exogenous latent variable, factors in the lower level, "inadequate supervision", etc., are considered to be the endogenous latent variables. The questions of each factor in the questionnaire served as the measured variables. In Fig. 6, the structure of the relationships between "organizational process" and factors in "unsafe supervision" level is shown. Relationships of the factors in other categories can be obtained in the same manner.

Using the AMOS 24 statistical package, the SEM can be constructed and analyzed easily. The message of "OK: Default model" showed in the
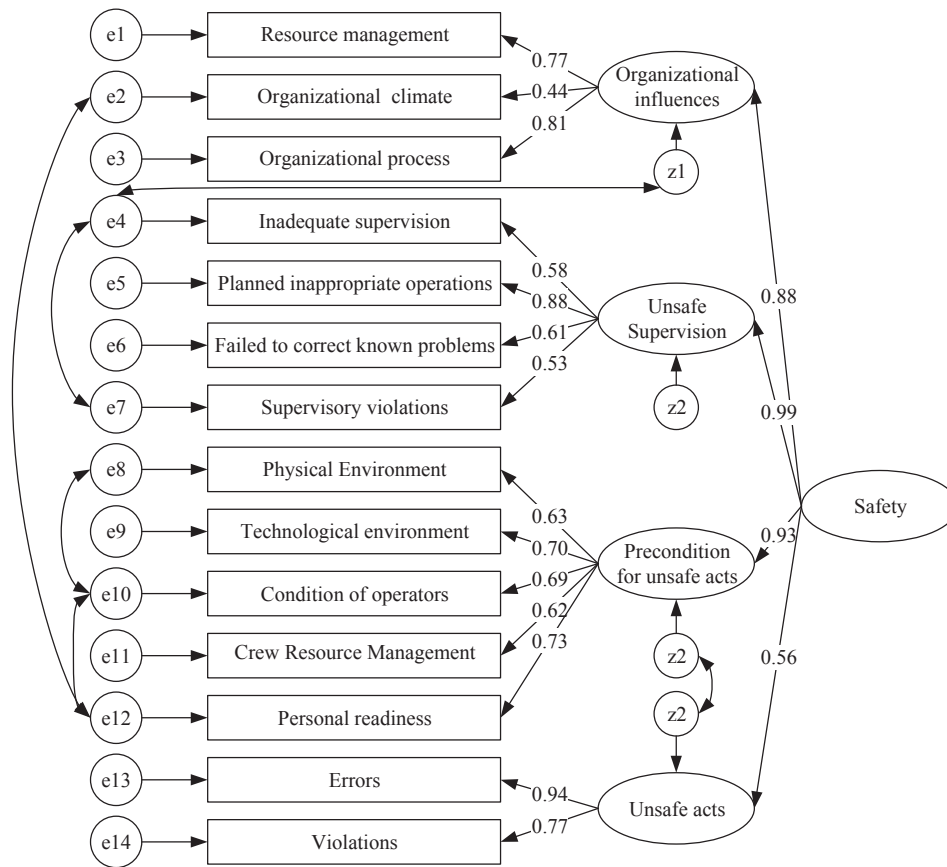
Fig. 5. SEM Model 1. The structure of second-order SEM used for analysis.

tool window means the model is successfully converged and identified. The value of "modification indices (MI)" given by AMOS 24 software can be used to modify and optimize the model. The pairs with high values are needed to build covariance, which can decrease the chi-square value. Based on the advice given by the value of MI, after several trials combining with the practical significance of the model to increase the correlation path, all of the scales meet the recommended levels. The

values of regression coefficients between factors are also shown in Figs. 5 and 6.

To give an overview of the results of SEM models, we describe the relationships of factors diagrammatically in Fig. 7. Variables where the arrow originated from them have high influence on variables receiving the arrow. The solid lines represent that the variables have the highest value in the same level, the dashed lines represent that the variables
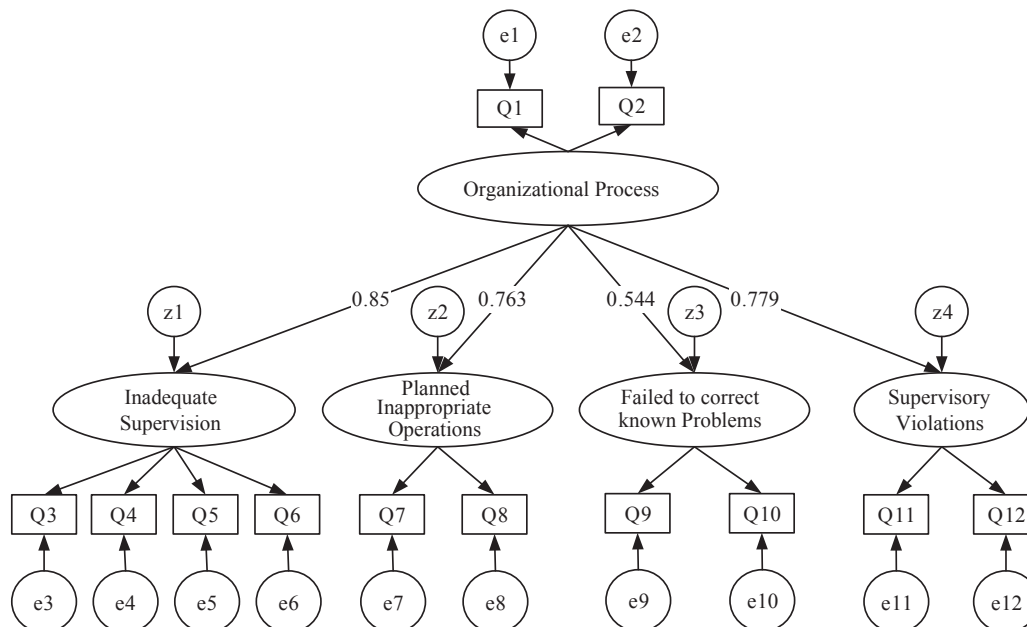

Fig. 6. SEM Model 2. The structure of the relationships between "Organizational Process" factor and the factors in "Unsafe Supervision" level.
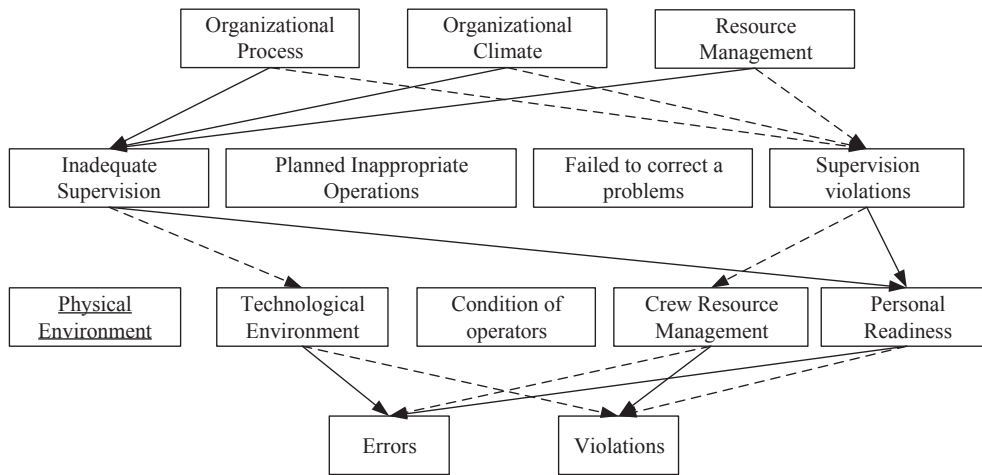
Fig. 7. The main regression coefficients of SEM Models.

have the second highest value, for example, in the SEM model 2, the regression coefficient between "organizational process" and "inadequate supervision" is the highest, so these two factors are linked by solid line, the regression coefficient between "organizational process" and "supervision violations" is the second highest, so they are linked by dashed line. Fig. 7 gives the influence chains from the causal factors to the largest and second largest consequent factors, thus safety recommendations could be proposed purposefully.

Although there are many different proposals on goodness-of-fit indices, Hair et al. (1998) divided the fit indices into three classes: absolute fit measurements, incremental fit measurements and parsimonious fit measurement. To reach consensus, the three categories are recommended to be considered at the same time. The thresholds and results of fit indices are shown in Table 3.

The overall fit statistics indicate a very good fit for the model, the absolute fit measurements, including root mean square residual (RMR), root mean square errors of approximation (RMESA), goodness-of-fit index (GFI) and adjusted goodness-of-fit index (AGFI), are in the recommended acceptable range. The incremental fit measurements, including normed fit index (NFI), relative fit index (RFI), incremental fit index (IFI), and comparative fit index (CFI), are mostly greater than 0.9. The parsimonious fit measurements, including parsimony goodness-of-fit index (PGI), parsimony-adjusted NFI (PNFI), are mostly greater than 0.5. In conclusion, these SEM models are acceptable.

3.4. Human factors importance priorities by ANP

The "Safety goal" with the four main categories forms the control level; sub-categories form the network level. We use the SuperDecisions

2.8 software to carry out the calculations in ANP; the structure of ANP is shown in Fig. 8. The goal points to the four main categories in the criteria level, and each criterion also points to its own factors. In the HFACS, factors in the higher level affect factors in the lower level. Correspondingly, factors in the higher cluster point to factors in the lower cluster.

As for the pairwise comparison, the regression coefficients obtained from SEM models can be used to give the judgments of comparisons. There are two situations existing in the comparison of two variables. When the coefficients of two variables are significantly different, for example, the coefficients between "safety goal" and "organizational influence" is 0.88, while the coefficients between "safety goal" and "unsafe supervision" is 0.99, we could consider "unsafe supervision" is more important than "organizational influence", and assign 5 in this comparison; When the coefficients of two variables are of little difference, for example, the coefficients between "precondition for unsafe acts" and "condition of operators" is 0.69, while the coefficients between "technological environment" and "precondition for unsafe acts" is 0.70, then we consider "condition of operators" is equally important with "technological environment", and assign 1 in this comparison. Once the comparison matrices are completed, supermatrixes, weighted supermatrixes and limit matrixes can be calculated by SuperDecisions 2.8 software automatically. The normalized result calculated from the limit matrix is shown as the results of SEM-ANP method in Table 4.

3.5. Frequency statistics

In order to verify and compare the method proposed in this study, the normalized weights calculated by frequency-based method are also

Table 3
The fitness of SEM models.

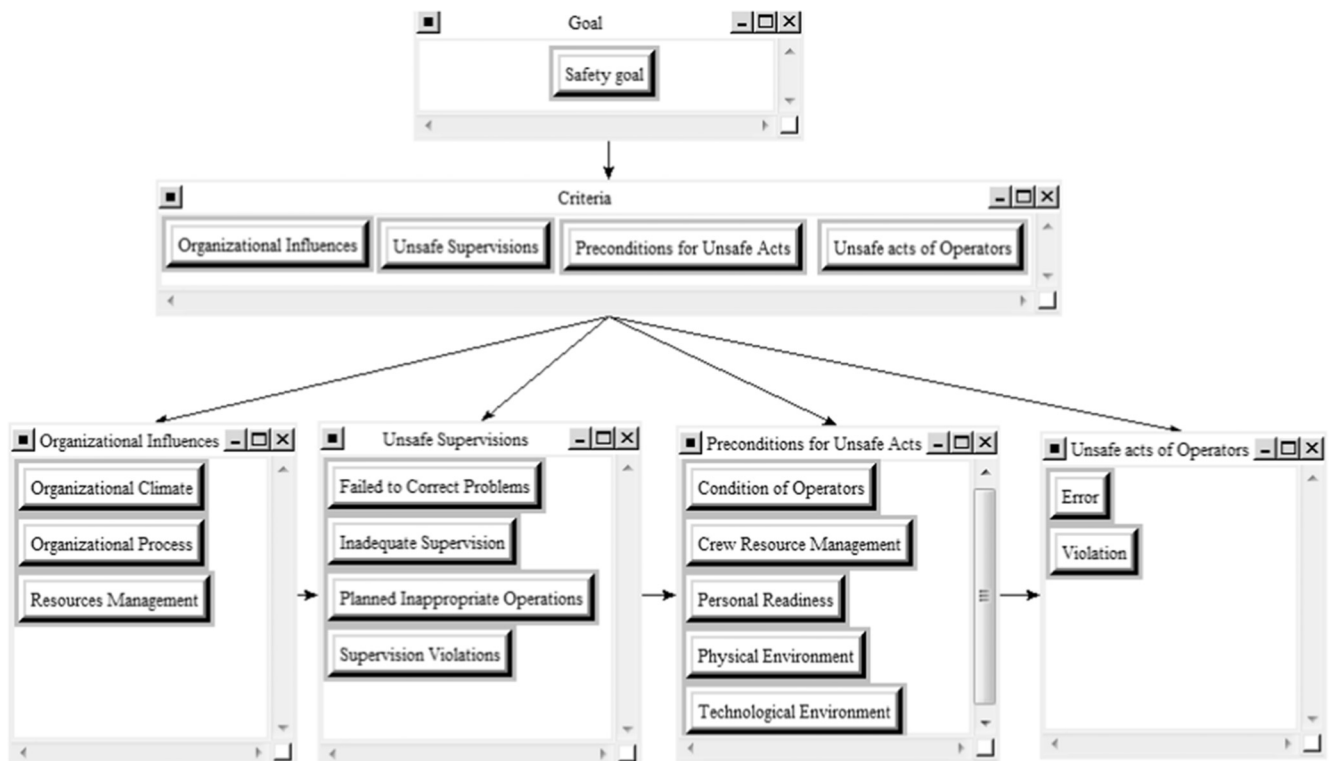| Metric	Threshold	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12	Model 13
Absolute fit measurements														
RMR	< 0.05	0.009	0.012	0.008	0.008	0.012	0.011	0.009	0.010	0.010	0.008	0.009	0.009	0.010
RMESA	< 0.08	0.071	0.062	0.055	0.054	0.062	0.056	0.044	0.049	0.075	0.064	0.061	0.071	0.076
GFI	> 0.9	0.929	0.935	0.950	0.955	0.929	0.934	0.952	0.942	0.961	0.969	0.968	0.963	0.957
AGFI	> 0.8	0.889	0.903	0.919	0.925	0.895	0.902	0.925	0.912	0.920	0.930	0.940	0.928	0.920
Incremental fit measurements														
NFI	> 0.9	0.927	0.924	0.901	0.906	0.911	0.918	0.939	0.926	0.964	0.962	0.959	0.950	0.954
RFI	> 0.9	0.901	0.912	0.863	0.867	0.884	0.892	0.917	0.901	0.941	0.932	0.939	0.922	0.931
IFI	> 0.9	0.954	0.911	0.945	0.949	0.946	0.954	0.974	0.964	0.976	0.977	0.976	0.967	0.968
CFI	> 0.9	0.953	0.909	0.923	0.948	0.946	0.954	0.973	0.963	0.975	0.977	0.976	0.967	0.968
Parsimonious fit measurement														
PGFI	> 0.5	0.593	0.627	0.647	0.577	0.628	0.629	0.611	0.623	0.470	0.431	0.516	0.492	0.511
PNFI	> 0.5	0.682	0.841	0.678	0.639	0.699	0.695	0.689	0.695	0.589	0.535	0.639	0.607	0.636

Fig. 8. The structure of ANP in SuperDecision software.

shown in Table 4. The accident investigation reports were collected from the famous Chinese oil enterprises, such as Chuanqing Drilling Engineering Company Limited and China National Offshore Oil Corporation. 128 accidents investigation reports were observed between 2001 and 2016. The collected cases are all personal casualty or significant property damage accidents.

According to the results of the frequency-based method in Table 4 and the influence chains in Fig. 7, the factors which are not only in high rank but also have strong inter-relationships are "organizational process", "personal readiness", "inadequate supervision", "supervision violations", "errors" and "violations". Moreover, to be concise, the main important observations of these five factors are listed in Table 5.

3.6. Discussion

The first six important factors shown in Table 5 is "personal readiness", "inadequate supervision", "supervision violations", "organizational process", "errors" and "violations", which are emphatically discussed below.

Inadequacies at "organizational influence" had associations with further inadequacies at "unsafe supervisions". Reason (1990) and Wiegmann and Shappell (2003) hypothesized that inappropriate decision-making by upper-level management can adversely influence the personnel and practices at the supervisory level, which in turn affects the psychological pre-conditions and hence the subsequent actions of the frontline operators. "Organizational process" is a particularly important factor and has a high ranking according to the results of the SEM-ANP method shown in Table 4, while in the frequency-based

Table 4
The results of SEM-ANP method and frequency-based method.

Main categories	Sub-categories	Results of SEM-ANP method		Results of frequency-based method		
		Weight	Rank	Number	Weight	Rank
Organizational influence	Organizational climate	0.0515	9	81	0.076	8
	Resource management	0.0494	12	39	0.036	12
	Organizational process	0.0957	4	65	0.061	9
Unsafe supervisions	Failed to correct known problems	0.0491	13	21	0.02	13
	Planned inappropriate operations	0.0505	10	64	0.06	10
	Inadequate supervision	0.1046	2	121	0.113	2
	Supervision violations	0.0982	3	103	0.096	5
Preconditions for unsafe acts	Personal readiness	0.168	1	123	0.115	1
	Crew resource management	0.0523	8	89	0.083	6
	Condition of operators	0.0345	14	3	0.003	14
	Technological environment	0.0554	7	89	0.083	6
	Physical environment	0.0504	11	56	0.052	11
Unsafe acts of operators	Violations	0.0585	6	108	0.101	4
	Errors	0.0816	5	109	0.102	3

Table 5
Observations and calculations of part factors.

Factors	Observations	Number	Observation ratio
Organizational process	Lack of risk management programs	52	0.515
	Failing to set clearly defined safety objectives	37	0.366
Inadequate supervision	Failing to provide skill and safety training and training track qualifications	98	0.386
	Failing to check the qualification of equipment	80	0.315
	Failing to provide planned control	59	0.232
Supervision violations	Disregard for existing rules, regulations	76	0.461
	Disregard for instructions by managers	74	0.448
Personal readiness	Lacking of safety awareness	117	0.483
	Lacking of experience and poor training result	102	0.421
Errors	Improper operation	47	0.346
	Omitted step in procedure	42	0.309
	Improper cognitions	36	0.265
Violations	Operation and maintenance not in accordance with the standards	94	0.563
	Not qualified for mission	61	0.365

method, the ranking of "organizational process" is relatively low. The first reason is that the empirical data used by frequency-based method is obtained from accident reports, and it is hard to dig the deep causes of accidents through accident reports. Some of the causes concluded from the accident reports are relatively superficial, giving expressions to superficial reasons instead of inherent reasons, focusing the direct causes of accident and omitting the influences of factors in the high levels. Over time and the multiple coupling of factors, from quantitative change to qualitative change, accident is caused by occasional factors randomly, and factors such as the physical environment are the incentives of the accident.

The second reason is that the effects of "organizational process" are taken into considerations by the SEM-ANP method, when the factors in the lower level occur. Li and Harris (2006a) suggest that accident investigations should be pursued further back into the organization. The weights of some factors in the high levels are increased, which is more consistent with the requirements of safety management.

Organization should attach importance to inadequacies in "organization process". According to the observation ratios obtained from accident reports shown in Table 5, the observations of inadequacies in "organization process" mainly include two aspects. The first one is the lack of risk management programs. Inadequacies of risk management programs may lead to the inadequacies of planned controls, recognitions and assessments towards risk factors, which can ulteriorly cause the lack of factors in the lower levels such as the lack of safety technical protections in "Technological Environment". Organization should conduct hazard identification and safety assessment in the lifting operations as per the requirements of crane or hoist management programs, set up the safety barrier and monitoring measures, and archive files of them. The dangers exist in many aspects of lifting operations including the installations of drawworks, crown blocks, and derricks, all of which need to be monitored and taken risk reduction measures specially. The second one is failing to set clearly defined safety objectives. Organization should set and decompose safety objects and indices according to the situations of safety works in the form of official documents and liability statements.

In "unsafe supervisions", "inadequate supervision" and "supervision violations" are the two important factors. Especially, "inadequate supervision" is the key factor at "preconditions for unsafe acts" level (Li and Harris, 2006a, 2006b). According to the observation ratios obtained from accident reports shown in Table 5, the observations of "inadequate supervision" mainly include three aspects. Failing to provide skill and safety training and training track qualifications is the first observation, having especially important impact on "personal readiness" as shown in Fig. 7. The lacks of skills and safety awareness in "personal readiness" both have close relationships with education

training and can cause errors and violations. Organizations should implement the training in accordance with the requirements of the safety training management system, and determine and conduct training needs of positions according to post capacity requirements. For example, new employees shall attend the Three Level Safety Training, namely at level of company, drilling crew and shift. They must pass the examination before taking the post; special safety education and training for personnel should be conduct before the applications of new craft, new technology, new material and new equipment. Operators who transferred and leaved more than one year should receive and pass safety education training. In particular, the drillers and assistant drillers on the drilling floor should be trained at least in risk management, well control, crane operation and slinging, advanced firefighting, basic first aid and health, safety and environment (HSE) management.

Failing to check the qualification of equipment is the second observation, which can lead to the inadequacies in "technological environment" and accordingly affect the safety. The drilling enterprise should implement quality control for the purchase of equipment and facilities, monitor installation procedure, check and confirm before the application. All equipment and tools must be checked for valid, safety and load testing certification. For example, the working load limit of the air winch should always be checked before hoisting any large or heavy equipment off the catwalk. All equipment and tools must be visually inspected for damage and/or wear prior to operation. For example, the driller shall ensure that all gauges and sensors, such as the weight indicator, torque gauge, are inspected and calibrated before starting the operation. Taking the safety operations and inspections of the masts or derricks as another example, prior to raising or lowering the mast, the crew should inspect drill line, raising line, sockets, pins, safety keepers, and hold-down bolts in mast shoes for damage. If damage is found, the mast should not be raised or lowered until corrective action is taken. The crew should inspect substructure, mast or derrick and replace missing pins, bolts and safety keepers each tour. The crew should record the inspection on the schedule for rig maintenance. Safety lines should be attached to all sheaves hanging in the derrick (i.e., tongs, air hoist/winch, catlines, etc.). These lines should be inspected frequently. Inspections of the masts or derricks should be performed periodically after commence of well operation. The derrickman should inspect the monkey board prior to the operation. Safety pins should be checked regularly to make sure they are properly secured. The pipe racking fingers should be kept straight and secured with a safety chains.

Failing to provide planned control is the third observation, having relationship with the setting of risk management programs. And it can result in failing to recognition of risk factors and then the inadequacies of corresponding protections in "technological environment". In the

accident reports, the "inadequate supervisions" and "supervision violations" are often mentioned. But tracing back to the root, factors in "organization influence" are the root causes. The influence chain, that "organization process" influence "inadequacies supervision", and then "inadequacies supervision" influence "technological environment", is shown in Fig. 7. Thus, in the SEM-ANP method, the weight of "technological environment" fall to the 7th, compared to the 6th in the frequency-based method. Organization should provide planned control on change of institution, personnel, process, technology, equipment, operating process and environment that is permanent or temporary change. It is necessary to identify the hidden dangers of lifting operations, and implement the corresponding planned control measures and preventions before the work. In the lifting operations, it is vital to specify planned control measures for blowout prevention, firing and poisonous gasses such as H_2S to guarantee safety operation in the under-balanced drilling design.

"Supervision violations" mainly includes the violations of supervisors. The fact that leaders neglect their duties will result in poor performances of work teams, which have an important impact on "personal readiness" and "crew resource management". More specifically, the irresponsibility is mainly shown in two aspects. The first one is the lack of guidance on operators' safety awareness and safety behaviors in "personal readiness". The crews must be guided to be aware of these hazards at all times. The leaders should keep the person outside of working staff from entering the dangerous area. For example, when someone is inside the loop of the drilling line during the activity of reeving in the drilling line to raise the mast, the supervisor should stop the dangerous activities. The supervisor should instruct to repair or replace worn, damaged or grooved catheads without delay.

The second one is the lack of communications and collaborations in work teams. Also in Fig. 7, "supervision violations" have influence on "personal readiness" and "crew resource management". According to "Standard Scoring Method for Safety Production of Drilling in Oil Industry" (SAWS, 2012), leaders should comply with the requirements of safety contact system to conduct communication and observation in the grassroots units. For example, a pre-job meeting with the crew and the crane operator should be held to discuss equipment, procedures and safety before starting the job during the work of running in and laying downdrill collars; When in the cathead operation, a qualified person should be at the driller's console to disengage the cathead in case of an emergency. During reeving on new drilling line on empty sheaves with a standing derrick, the derrick man, positioned at the crown block, should advise the driller when the snake is coming through the crown sheave. The driller and the derrick man must remain in constant radio contact.

In "preconditions for unsafe acts" level, "personal readiness" ranked first in the two methods, indicating that "personal readiness" is the key link point between operation and supervisory. As discussed in "unsafe supervisions" level, the lacking of safety awareness in "personal readiness" is influenced by many upper human factors, such as failing to provide education training in "inadequate supervisions", incompetence of leaders in "supervision violations" etc. Lacking of experience and poor training result are also influenced by education training. The production operators and inspectors should, before taking their posts, accept trainings and examination which should be limited to the specific type equipment he/she will operate. Each personnel should have acquired a corresponding certificate before on duty. The drillers and assistant drillers should, before taking their posts, accept trainings and examination. Operators should never visit others at work hours, leave working post without permission, work after drinking.

"Unsafe acts of operators" acts as the final level related with the accident directly. "Errors" and "violations" are both highly ranked in the two methods, shown in Table 4. Accidents are rarely caused by just one single error (Li and Harris, 2006a). As shown in Fig. 7, "technological environment", "crew resource management" and "personal readiness" have strong effect on "errors" and "violations". As an

example, the drilling tool is stuck when lift up the drilling tools. The operators take inappropriate measures, such as lifting the drilling tool to a high tonnage level at one-time force, instead of lifting step by step or back reaming, and finally the drilling tool is damaged. The direct causes are lack of analysis of the underground conditions and the inappropriate measures. The indirect causes in charge of this accident mainly include three aspects. The first cause is the lack of skills and safety awareness in "persona readiness"; the second cause is the lack of protection measures in "technological environment"; the third cause is the poor management of team work in "crew resource management". Over time, the indirect causes will transform into direct causes and result in accidents. Thus, preventions and managements should be carried out from organization level. Li and Harris (2006a) suggest that the interventions at "unsafe acts of operators" level and "preconditions for unsafe acts" level would only have limited effects in improving overall safety. As an example, measurements which aim at the skill errors of operators cannot solve the inadequacies in other aspect, like violations and inadequate technical protections. Furthermore, the improvements of skills need the support of education training in "inadequate supervisions". Therefore, organization should attach more importance to the management of factors in the high levels (for example, "organizational process" "inadequate supervisions" and "supervision violations"). Although measures only aiming at the lower levels have limited effects, the specific errors and violations can act as guide to rectification, such as the focuses of education training, and technical protection. For example, in dealing with the sticking of drill tools, operators often lift the drilling tools to a high ton level at one-time force, therefore the appropriate measures, such as lifting gradually, and back reaming, should be educated emphatically at times. Any safety deficiencies or violations must be corrected immediately before proceeding with lifting operations.

In all, there is no easy way to improve the situation of safety work, as coupled and complex problems from many aspects need to be taken into consideration. However, it could be safer and more effective to enhance the factors and categories discussed above.

We propose a hybrid method which combines multi-SEMs with ANP to take numerous opinions into consideration for the reduction of assessment biases. The empirical study in oil drilling work system shows that the proposed hybrid method is suitable and effective. However, the proposed method is complex, of which the process is time-consuming. There are still other methods that could reduce the experts' subjective biases and support AHP or ANP, like multi-dimensional scaling technique, known as the Sammon map (Condon et al., 2003). We will work further to explore more convenient methods which can be combined with AHP or ANP.

4. Conclusion

We provided an understanding, based upon empirical study, of how actions and decisions at the higher organizational and managerial levels in oil and gas industry result in errors and violations. The results showed causal paths that relate errors and violations at operation level with inadequacies at both the immediately adjacent and higher levels. This study drew a clear picture that supports Reason's (1990) model of active failures resulting from latent conditions in the organization. After the comparison with the frequency-based method, the results showed that the SEM-ANP method can reduce the biases of experts and provide more reasonable and comprehensive assessment. Observations by the frequency-based method from accident reports were also analyzed, and the specific and feasible recommendations are given.

The results showed that "organizational process", "inadequate supervisions", "supervision violations", "personal readiness", "errors" and "violations" are the factors which have more important influences on safety work. And investments in "organizational process", "inadequate supervisions" and "supervision violations" can be more efficient. Especially, the improvement of "organizational process" can reduce the

"inadequate supervisions" and "supervision violations". The managements in "inadequate supervisions" and "supervision violations" can improve the situations of "personal readiness", "technological environment" and "crew resource management", and therefore can reduce the occasions of "errors" and "violations". Interventions at "unsafe acts of operators" level and "preconditions for unsafe acts" level would only have limited effects on improving the overall safety. After all, improving the factors in the lower levels depends on the factors in the higher levels. As the root, factors in the higher levels, such as "organizational process" and "inadequate supervisions", play an important role. Therefore, organizational can strengthen the governance of factors in the higher levels based on holistic considerations.

Acknowledgement

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