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Risk assessment for a floating attitude tension leg platform by application of a hybrid fuzzy-statistical process control model

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Abstract: This paper proposes a risk assessment approach for a tension leg platform (TLP), named hybrid fuzzy-statistical process control (SPC) model, which provides more precise estimation than other commonly used methods. The hybrid fuzzy-SPC model is designed to follow risk source identification and establishment of risk index groups. It has three components: fuzzy comprehensive evaluation method, analytic hierarchy process (AHP), and SPC theory. In comparison to applying only one of the three, the hybrid fuzzy-SPC model usually results in reduction in uncertainties and subjectivities. The fuzzy comprehensive evaluation method and the AHP are used to obtain several independent risk evaluation scheme results. Then, based on the SPC theory, a practitioner is able to derive a confidence interval using the central limit theorem. This will largely mitigate risks and enable preventive action before a platform loses floating attitude.

Key words: Tension leg platform (TLP); Risk assessment; Floating attitude; Hybrid model; Fuzzy-statistical process control (SPC)
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1 Introduction

Oil is the lifeblood of the economy, making a stable supply of oil imperative. With numerous untapped sources of oil in the deep ocean, many companies are investing in deep ocean marine energy exploration and drilling. One of the greatest challenges of deep-water marine energy exploitation is maintaining adequate attitude for deep ocean marine platforms. Currently, tension leg platforms (TLPs), semi-submersible platforms, and spar platforms are the primary means of maintaining attitude.

Of these three attitude types, TLP is the focus of this paper. TLP is a marine oil and gas mining structure comprising of a primary working superstructure, one or more support pontoons, and a tension leg mooring system. The tension leg mooring system, which provides motion control, consists of numerous cables that moor the TLP to the ocean floor.

It is widely known that a good floating attitude is conducive to the work efficiency of TLP. During the service life of a TLP, it may encounter various sea states, placing various extreme stresses on the tension leg mooring system. In the event of failure of that system, the TLP will lose positional control and stability control, likely to be followed by loss of floating attitude. Therefore, it is important to ensure that the tension leg mooring system remains intact, and that crew are skillful and energetic. By performing appropriate risk assessment, risks arising from sea states, structure, and crew will be eliminated.

When the platform is in the initial design phase, engineers need to properly explore possible risk

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factors. Proper use of risk analysis, early in the design process, will result in reduced risk of rework, unforeseen problems, and possible system failure. Additionally, this risk assessment approach could be used to modify existing designs to improve their safety and reliability.

2 Research status

Risk assessment is necessary for offshore engineering projects to improve the performance and secure the success of the projects (Liu et al., 2013). A variety of techniques are proposed in the literature, including fuzzy theory, Monte Carlo simulation, analytic hierarchy process (AHP)/analytic network process (ANP), fuzzy AHP/fuzzy comprehensive evaluation, and probability-impact models, which are used to assess a project's risk and evaluate performance (Coelho et al., 2005; Taroun et al., 2011; Chen et al., 2015). A lot of methodologies based on the fuzzy theory, an effective tool to deal with subjective judgement, have been presented. They convert the uncertainties in assessment to a quantification, and are an important step to parameterize the assessment model. A summary of these research papers is given below:

(a) Nieto-Morote and Ruz-Vila (2011) presented a risk assessment methodology based on the fuzzy sets theory and AHP. This was done using an algorithm to handle the inconsistencies in the fuzzy preference relation when pair-wise comparison judgements were necessary and used trapezoidal fuzzy numbers until the defuzzification step.

(b) Zeng et al. (2007) presented a new risk assessment methodology to cope with risks in complicated construction situations. Fuzzy reasoning techniques and modified AHP were applied.

(c) Wang et al. (2015) assessed operational ocean observing equipment by application of a fuzzy comprehensive evaluation model. The evaluation index system was developed and included four factors: intrinsic performance, operational reliability, operational stability, and entire cost, as well as 11 sub-indices.

(d) Yang and Wang (2015) established a framework for analyzing and synthesizing engineering system risks on the basis of a generic fuzzy evidential reasoning (FER) approach.

(e) Sadiq et al. (2004) established a framework for a risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique.

(f) Mentes and Helvacioglu (2011) presented a methodology of fuzzy fault tree analysis (FFTA) and combined the effects of operational failures and human errors under a fuzzy environment, which was more flexible and adaptive than conventional fault tree analysis (FTA) for fault diagnosis and hazard estimation.

(g) Fattahi and Khalilzadeh (2018) proposed a novel fuzzy hybrid method for failure mode and effects analysis (FMEA) to evaluate various failure modes more precisely. In this method, the fuzzy weighted risk priority number was considered. The weights of the three factors and the weights of failure modes were computed by extended fuzzy AHP and fuzzy MULTIMOORA methods, respectively.

Statistical process control (SPC) is a method of quality control that employs statistical methods to monitor and control a process, and is never used for risk assessment. It can supplement the deficiency of fuzzy theory in risk assessment. The methodologies based on fuzzy theory and AHP/ANP only solve the quantification of risk factors, but cannot facilitate the treatment of subjective factors in the assessment process. SPC is based on multivariate statistical projection methods (principal component analysis (PCA) and partial least squares (PLS)). It can figure out the assessment result as within the control limit with established evaluation schemes by controlling the assignable variation to reduce the impact from subjective factors to make the risk assessment much more convincing. A summary of research is given below:

(a) MacGregor and Kourti (1995) used multivariate control charts in the projection spaces providing powerful methods for both detecting out-of-control situations, diagnosing assignable causes, which was applicable to both continuous and batch processes.

(b) Sohn et al. (2000) focused on applying an SPC technique known as an "X-bar control chart" to vibration-based damage diagnosis. A statistically significant number of features outside the control limits indicate a system transition from a healthy state to a damage state. A unique aspect of this study is the coupling of various projection techniques with the SPC in an effort to enhance the discrimination between features from the undamaged and damaged structures.

As well as the methodologies mentioned above, there are a couple of other ways to assess risk. The dynamic parameter fusion method of risk evaluation is used to prevent random risk and to improve the evaluation based on multi-scale, multi-source, real time, and recursion data (Liu, 2013). The semi-quantitative (Chen and Zhou, 2014), comprehensive risk evaluation (Jing, 2007), and probability distribution (Osborn and Millwater, 2005) methods are also useful to engineering projects.

In offshore engineering projects, there are many risks threatening their safety. For example, an offshore platform normally is exposed to flammable oil and gas in the course of its operation. A fire accident represents a major part of the total risk to offshore platforms. A new fire risk analysis (FRA) procedure has been developed, which has two advantages: first, effective structural consequence analysis without the need for design accidental loads (DALs), and second, probabilistic safety assessment subjected to a certain number of prescribed fire-accident scenarios. The cumulative failure frequency becomes useful information for determination of risk mitigation measures (Jin and Jang, 2015). Additionally, the mooring system is a potential risk for offshore platforms (Yang et al., 2015). Research focuses on minimizing the catenary mooring system weight of a floating wind turbine with a tri-floater semi-submersible support structure, with reference to ultimate and accidental loads (Benassai et al., 2014).

Most research focuses on the mooring response, risk, and project management for offshore structures. There is little research on assessing the risk associated with the mooring system and hull, which determines the floating attitude of the marine platform. Additionally, risk assessments are generally based on the methodologies of fuzzy theory and AHP/ANP, which are not sufficient methods to assess risk under all conditions. Other statistical methods are qualified to fully assess risk. To overcome the imperfections mentioned above, this paper proposes a hybrid fuzzy-SPC model for risk assessment of floating attitude, combined with a fuzzy comprehensive evaluation method, AHP and SPC theory. The advantage of the proposed methodology is the application of SPC theory, which makes the assessment based on the fuzzy comprehensive evaluation method and AHP more effective and efficient.

3 Methodology of risk assessment

In engineering projects, risk refers to the likelihood of deviation from the expected work conditions due to uncertainty. Uncertainty is the state of deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood (ISO, 2009a, 2009b). There are many uncertainties involved in the operation of engineering projects, such as unpredictable weather conditions and improper maintenance or operation. When an unexpected breakdown occurs, there is little response time for risk management. Therefore, it is important to assess risks and offer adequate warning as early as possible.

Risk assessment is the overall process of risk identification, risk analysis, and risk evaluation. It is the scientific determination of quantitative or qualitative estimate of risk related to a well-defined situation and a recognized threat based on data and operating experience to understand the risk and its potential impact on objectives. To identify the contributors to risks and weak links in system and organizations, it is feasible to calculate the marginal effect of changing parameters that drive the change of risk, find out the most sensitive parameters and their critical points (the first derivative equaling zero), and predict the possible risks based on dominantly sensitive parameters (the parameters that mostly dominate the magnitude of risk). After the sensitivity analysis, risks are prioritized. It provides reliable basis for scientific decision-making in risk management and takes reasonable action to achieve effective risk reduction with limited input. Therefore, managing the risk identified from known data and operational experience in advance based on risk assessment will have a great impact on the efficiency of platform operation.

The methodology of risk assessment has three parts. The first part is risk identification, which includes: (1) identifying the causes and source of the risk which could have a material impact on objectives and the nature of that impact; (2) classifying the causes and source of the risk as risk indices. The second part is risk analysis, which includes two steps: step one, establishing evaluation risk index group (abbreviated as risk index group) based on risk indices (Fig. 1); step two, proposing evaluation scheme with the approach which is suitable for the well-defined risk index group. The last part is risk evaluation with the risk index group and the evaluation scheme. This paper focuses on the second and last parts that establish a well-defined risk index group suitable for TLP and a novel assessment approach.

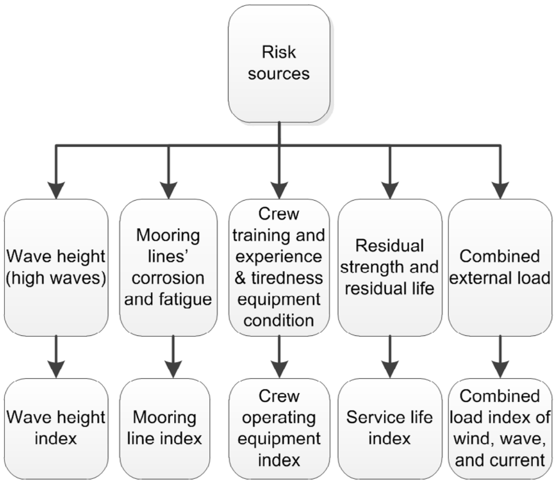

Fig. 1 Risk index hierarchy

4 Identifying the risk to establish evaluation risk index group

The first step of the risk assessment process is risk identification. Risk identification entails studying a situation to assess what could go wrong in project development at any given point of time. This process must involve an investigation into all the potential sources of project risks and their consequences (Carr and Tah, 2001). In this case, floating attitude can be influenced by various factors, including environmental conditions, mooring system, support structure, and crew operation of the offshore platform.

To address the different risks involved in designing an offshore platform, the construction of a risk index hierarchy (Fig. 1) is used, which combines all the factors and sub-factors specific to the problem (Chen et al., 2015). The purpose of a risk index hierarchy is to decompose risk factors into adequate detail, in which a risk index can be efficiently assessed (Zeng et al., 2007). All risk indices are necessary to form an evaluation risk index group for the assessment. The evaluation risk index group is the junction between risk sources and risk assessment. A risk index group comprises various independent risk indices and should reflect all the objectives of the problems which are required to be solved. A risk index group should be practical, complete, reasonable, scientific, and basically acceptable to most decision-makers. The uncertainty of risk increases the complexity of the assessment, such that many indices need to be evaluated (various risk factors to determine risk index group), multi-objective for evaluation (multiple needs and goals), non-uniqueness for risk level (multiple acceptable risk tolerance), complexity for re-evaluation (multiple evaluation schemes), and variable correlation for risk indices (dependent risk factors). Choosing the most important risk indices that threaten a TLP floating attitude in establishing a risk index group is a major topic.

The internal and external hazards that affect TLP safety in service are various (Hu et al., 2012), including:

(1) Environmental conditions, including wave height, wavelength, wave period, wave energy distribution, wind speed and direction, current speed and direction, local sea salinity, local temperature, and severe environment;

(2) Characteristics of the tension leg mooring system to include corrosion condition of mooring lines, and their quantity and configuration;

(3) Platform support structure condition;

(4) Crew operational routine and experience;

(5) Service life.

In risk assessment, it is not feasible to consider all impact factors for two reasons. First, it is time-consuming if all the impact factors are considered, as that makes the assessment more complex. Second, some variables are dependent, combining these variables into one index to represent a similar risk. For example, wave period and wave frequency are similar parameters related to wavelength, one of the most important parameters in determining wave power. It is apparent that using a wave period index, instead of using three indices, to represent wave power is simpler.

The complexity of risk assessment is mainly rooted in the establishment of a risk index group (Wang et al., 2007). For TLP service in the ocean, the major risks that affect floating attitude have six parts: (1) wave condition (wave height and wave period); (2) wind, current and the combined load of wind, wave, and current; (3) work position (in sheltered, inshore or offshore waters), related to the water depth; (4) mooring system; (5) residual strength of platform (related to the service life); (6) crew operation and equipment condition. These risk indices are independent, not repeated, and cover most of risk factors (environment, structure, and crew) for risk management that a TLP may meet when operating in the ocean.

Significant risks to the TLP result from the alternating load caused by the ocean environment. Waves interact with the TLP, transferring energy. This transferred energy is commonly referred to as wave power. This wave power constitutes the primary risk to floating attitude. For both regular and irregular waves, wave power is determined by wave height and wave period. Therefore, the wave height index and wave period index are the most important indices.

Wind and current are significant loads on TLPs. The combined load of wind, wave, and current can lead to excessive environmental loads. Using a harsh environment index, a combined load index of wind, wave, and current, can represent the risk from wind and current in their combined form. This risk is significantly increased if the TLP is located in sheltered, inshore or offshore waters.

In general, water depth increases with distance from the coast. The load condition of tendons changes with increasing water depth, affecting the station-keeping ability of the platform. Concurrently, the complexity and unpredictability of weather conditions increase, with distance from the coast. Using an operational water depth index accounts for the risk associated with the TLP's position relative to the coast.

The mooring system is essential, and has a significant impact on the floating attitude stability of a TLP. Initial physical condition (mooring line stiffness index) and current condition (mooring line index) represent the risk from the mooring system.

Other risk indices include the residual strength of the platform structure. This affects the safety of the TLP, and has an impact on the risk of floating attitude. Service life index represents the influence of the residual strength of the platform structure and is affected by the structure's working hours. Crew operation and equipment condition are also vital to keep the stability of the floating attitude. The crew operating equipment index represents the probability of an accident due to improper maintenance or operation of the TLP.

Combined with the analysis of risks that threaten the stability of floating attitude and using the experience of risk assessment of other marine vessels and offshore structures, this study presents a suitable evaluation risk index group based on the effective mooring recommended (CCS and OCIMF, 2015). The risk index group mainly consists of 10 indices, defined below:

(1) Wave height index R_{H}

This index is a ratio of significant wave height relative to the design wave height. For regular waves, wave power is $P=1/8\cdot\rho gH^2c_{\mathrm{g}}$, where ρ is the sea density, g is the gravitational acceleration, H is the wave height, and c_{g} is the wave group velocity (Dean and Dalrymple, 1991). For irregular waves, wave power is $P=(\rho g^2)/(64\pi)\cdot H_{\mathrm{s}}^2T_{\mathrm{e}}$, where H_{s} is the significant wave height, and T_{e} is the wave energy period (Flocard and Finnigan, 2010). For both regular and irregular waves, wave power is proportional to the square of the wave height. Because wave height is a second-order term in wave power, it is one of the most important parameters in determining wave power. Wave height index represents the magnitude of wave power relative to design condition. The greater the wave power, the greater potential threat to the floating attitude. This index belongs to positive risk: the smaller the value, the better.

$$R_{\mathrm{H}}=\frac{H_{1/3}^2}{H_0^2}, \tag{1}$$

where $H_{1/3}$ is one third of the highest waves in m; H_0 is the design condition of wave height, like the maximum wave with 100-year return condition in m.

(2) Wave period index R_{P}

This index is a ratio of wave period relative to the design wave period. For regular waves, wave power is proportional to wave group velocity, which is related to wave period (Dean and Dalrymple, 1991). For irregular waves, wave power is proportional to wave period (Flocard and Finnigan, 2010). Wave period is one of the main parameters in determining wave power. On the other hand, wave period is related to wave frequency, which affects platform response motion directly by frequency domain. If a wave period is close to the platform's natural period, the platform's motion response is severe. Wave period index not only represents the magnitude of wave power relative to the design condition, but also determines the platform motion response magnitude through a response function with frequency as a parameter. The greater the wave power, the greater potential threat to floating attitude and mooring system. This index belongs to positive risk: the smaller the value, the better. If the wave period is close to the platform natural period, the penalty coefficient is required.

$$R_{\mathrm{P}} = \frac{TX_{\mathrm{P}}}{T_0}, \tag{2}$$

where T is the wave period in s; T_0 is the design condition of wave period in s; X_{P} is the penalty coefficient. In the frequency domain, the maximum response motion magnitude is fewer than 10 times the minimum response motion magnitude with six degrees of freedom motion for the TLP (Kurian et al., 2008; Yan and Ou, 2010). If the wave period is close to the TLP's natural period, the value of the penalty coefficient is 10. If the wave period is far from the TLP's natural period, response motion is normal without large amplitude motion, and the penalty coefficient is not necessary. The configuration of response amplitude operator (RAO) is like a triangle, so mid-frequency approximates half the maximum. For simplicity, the rest of the penalty coefficient is 5 or 1. T_{n} is the TLP's natural period, calculated as

$$T_{\mathrm{n}} = 2\pi\sqrt{m/k}, \tag{3}$$

where k is the stiffness coefficient; m is the mass.

For simplicity, X_{P} is defined as a step function:

$$X_{\mathrm{P}} = \begin{cases} 1, & \text{if } T \le 0.4T_{\mathrm{n}}, \\ 5, & \text{if } 0.4T_{\mathrm{n}} < T \le 0.8T_{\mathrm{n}}, \\ 10, & \text{if } 0.8T_{\mathrm{n}} < T \le 1.2T_{\mathrm{n}}, \\ 5, & \text{if } 1.2T_{\mathrm{n}} < T \le 1.6T_{\mathrm{n}}, \\ 1, & \text{if } T > 1.6T_{\mathrm{n}}. \end{cases} \tag{4}$$

(3) Mooring line index R_{M}

This index represents mooring line corrosion and fatigue in the service period. Mooring lines are in tensile state perennially under water, and their inside tensile stresses are very large because the platform's huge buoyancy makes them stretch. Mooring lines are surrounded by sea water, and their work environment is complex. They suffer from the corrosive effects of sea water and alternating load of currents like vortex induced vibration (VIV), and drift force. Damage is prone to come from external corrosion and fatigue loading. Corrosion decreases mooring lines' diameter. Fatigue makes mooring lines easy to be fractured with small external loading, because the crack propagation decreases the effective mooring lines' diameter. The pitting intensity (represented by pitting area A), pitting depth (h), and diameter of mooring line directly present the situation suffered from corrosion and fatigue. A and h determine the corroded volume loss together $\Delta V=\sum_{i=1}^{P} c_i A_i h_i$, where i is the ith pitting corrosion; P is the population of pitting corrosion; c is cylindrical coefficient; A should be less than 30% of body's initial area, A_i is the ith pitting area in m^2; h should be less than 50% of body's initial thickness (Zhang, 2011), h_i is the ith pitting depth in mm. As working hours grow, effective mooring lines' diameter decreases, but ΔV increases, because of the loading suffered from corrosion and fatigue. This index belongs to negative risk: the greater the value, the better. If the wave period is close to the mooring lines' natural period, the penalty coefficient is required.

$$R_{\mathrm{M}} = \left(\frac{0.25D_0}{\frac{1}{P}\sum_{i=1}^{P} h_i} \cdot \frac{0.075\pi D_0^2}{\sum_{i=1}^{P} A_i} + \frac{D}{D_0} \right) \frac{1}{X_{\mathrm{M}}}, \tag{5}$$

where D is the mooring line diameter in current in m; D_0 is the design condition of mooring line diameter in m; $\frac{1}{P}\sum_{i=1}^{P} h_i$ is the average of pitting depth; $\sum_{i=1}^{P} A_i$ is the total pitting area; X_{M} is the penalty coefficient. In the time domain, the range of maximum response motion magnitude is less than 10 times the range of minimum response motion magnitude with transverse motion for mooring lines under tension (Simos and Pesce, 1997; Chatjigeorgiou and Mavrakos, 2002). If the wave period is close to the mooring lines' natural period, the value of the penalty coefficient is 10. If the wave period is far from the mooring lines' natural period, the response motion is normal without large amplitude motion, and the penalty coefficient is not necessary. The configuration of RAO is like a triangle, so mid-frequency approximates half the maximum. For simplicity, the rest of the penalty coefficient is 5 or 1. T_m is the mooring lines' natural period, calculated as $T_m = 2\pi\sqrt{(m_m + A_m)/k_m}$, where k_m is the mooring lines' stiffness coefficient, m_m is the mooring lines' mass, and A_m is the mooring lines' added mass. For simplicity, X_M is defined as a step function:

$$X_M = \begin{cases} 1, & \text{if } T \le 0.4T_m, \\ 5, & \text{if } 0.4T_m < T \le 0.8T_m, \\ 10, & \text{if } 0.8T_m < T \le 1.2T_m, \\ 5, & \text{if } 1.2T_m < T \le 1.6T_m, \\ 1, & \text{if } T > 1.6T_m. \end{cases} \tag{6}$$

(4) Crew operating equipment index R_{CE}

This index represents the probability of an accident due to improper maintenance or operation of the TLP. This index is associated with whether the crew are regularly trained and experienced, and whether equipment is in good condition. Operators play a key role in operating safely for the TLP, and their improper operation may lead the TLP to dangerous situations, like improper operation of ballast water, or improper hoisting deck and outfitting machinery. Another negative effect on the crew is tiredness. The workdays of crew continuous working at sea are an effective way to measure the tiredness. During the crew's service period, crew are energetic when they start their shift; after a couple of days, they would feel a little tired, and would be more prone to making errors; in the final days of their shift, they are even more tired than before, and have a high probability of making mistakes. Regular training, rich experience and tiredness of crew altogether affect operation safety. The valid maintenance of equipment is also essential for the safety of a TLP. The crew operating equipment index includes two parts, one is the factor of crew, and the other is equipment. These two parts determine the index together with half influence each. This index belongs to negative risk: the greater the value, the better. A larger index value represents that crew are more skillful and energetic. Also equipment is more validly maintained and in good condition.

$$R_{CE} = C_C C_T + C_E, \tag{7}$$

where C_C is the crew training and experience index; C_T is the crew tiredness index (C_C and C_T both reference the crew's experience); C_E is the equipment impact index.

$$C_C = \begin{cases} 0.5, & \text{if training twice one year,} \\ 0.4, & \text{if training once one year,} \\ 0.3, & \text{if training once one year and a half,} \\ 0.2, & \text{if training once two years,} \\ 0.1, & \text{if training once two years and a half,} \\ 0, & \text{if training once three years or more,} \end{cases}$$

$$C_E = \begin{cases} 0.5, & \text{if overhaul maintenance once one month,} \\ 0.4, & \text{if overhaul maintenance once two months,} \\ 0.3, & \text{if overhaul maintenance once three months,} \\ 0.2, & \text{if overhaul maintenance once four months,} \\ 0.1, & \text{if overhaul maintenance once five months,} \\ 0, & \text{if overhaul maintenance once six months or more,} \end{cases}$$

$$C_T = \begin{cases} 1.0, & \text{if continuous working less than two weeks,} \\ 0.9, & \text{if continuous working less than three weeks,} \\ 0.8, & \text{if continuous working less than four weeks,} \\ 0.7, & \text{if continuous working less than five weeks,} \\ 0.6, & \text{if continuous working less than six weeks,} \\ 0.5, & \text{if continuous working less than seven weeks,} \\ 0.4, & \text{if continuous working less than eight weeks,} \\ 0.3, & \text{if continuous working less than ten weeks,} \\ 0.2, & \text{if continuous working less than twelve weeks,} \\ 0.1, & \text{if continuous working more than twelve weeks.} \end{cases}$$

(5) Service life index R_{SL}

This index represents the influence of the residual strength of the platform structure affected by residual life in the TLP's service period. Residual life could not determine risk level directly, but it is related to residual strength. Although a platform's residual strength always satisfies the minimum requirements in service period, residual strength decreases as service time increases, and is below the residual strength of new construction because of corrosion and fatigue. Because of the uncertainty loads from the environment, what might happen is not predictable, like a structure designed for survival conditions of wave with a 50-year return condition is exposed to wave with a 100-year return condition. Although residual strength still satisfies the requirement, a large or coupled load beyond the design condition makes the platform more dangerous, as a result of the loads uncertainty. Rules are based on calculations and statistics, and they cannot ensure the absolute security of structures that satisfy the requirement. The residual strength increasingly becomes one of the main factors affecting the safety of a TLP in the final stage of the designed period of service. This index is a ratio of residual strength at the current stage relative to the new construction to represent what level of residual strength is remaining. An implementation of equipment index prevents destruction from an external force that is beyond the design condition. This index associates strongly with severe weather. It belongs to negative risk: the greater the value, the better. The larger value represents that TLP is close to new construction condition, sufficient residual life remains, and there is sufficient residual strength to ensure safety for service.

$$R_{\mathrm{SL}}=\frac{S_{\mathrm{R}}+(S_0-S)}{S_{\mathrm{R}}+S_0}, \tag{8}$$

where S_{R} is the remaining service life that is beyond the design period of service condition, whose residual strength also meets the requirement of rules in years; S is the life that TLP has served in years; S_0 is the designed service life of TLP in years.

(6) Combined load index of wind, wave, and current R_θ

This index represents the influence of the external force from ocean environment on the TLP floating attitude. The combined load of wind, wave, and current can lead to excessive environmental loads. These three types of loads may be in the same direction or different directions. Generally, if a TLP suffers wind, wave, and current loads from different directions, loads could offset each other in each of the direction components, so the actual load on the TLP may be less than the maximum of the three types of loads. If the TLP suffers wind, wave, and current loads from the same direction, the actual load on the TLP is likely to be far greater than any of these three types of loads. The most dangerous condition is that the TLP suffers wind, wave, and current loads in the same direction at the same time. The combined influence of any of two loads on TLP is no more than 1, and decreases as loading angle increases. This index belongs to positive risk: the smaller the value, the better. The R_θ coefficients are given in Table 1.

If one load direction is fixed, i and j represent the other two loads, respectively. In the fixed current direction, i=wind, j=wave; in the fixed wind direction, i=wave, j=current; in the fixed wave direction, i=current, j=wind.

Table 1 R_θ coefficients corresponding of two angles among wind, wave, and current loads

θ_{ij}	R_θ					
	15°	30°	45°	60°	75°	90°
15°	1.0	0.9	0.8	0.7	0.6	0.5
30°	0.9	0.8	0.7	0.6	0.5	0.4
45°	0.8	0.7	0.6	0.5	0.4	0.3
60°	0.7	0.6	0.5	0.4	0.3	0.2
75°	0.6	0.5	0.4	0.3	0.2	0.1
90°	0.5	0.4	0.3	0.2	0.1	0.1

θ_{ij}: loading angle, the angle among wind, wave, and current loads

(7) Operational water depth index R_{D}

This index represents the influence of water depth on stability in the TLP's service period. The risks of floating attitude are significantly increased if the TLP is located in sheltered, inshore or offshore waters. In general, water depth increases with distance away from the coast. The normal operational water depth of a TLP is 450–1070 m. Because tendon length increases as water depth increases, the problem of the potential excessive weight of long tendons emerges. The load condition of tendons changes with increasing water depth, affecting the station-keeping ability of the platform. Concurrently, the complexity and unpredictability of weather conditions increase with distance from the coast. Using the operational water depth index accounts for the risk associated with the TLP's position relative to the coast. The index belongs to positive risk: the smaller the value, the better. The smaller the operation water depth, the more stable is the platform.

$$R_{\mathrm{D}}=\frac{d}{d_0}, \tag{9}$$

where d and d_0 are the operation water depth and the maximum operation water depth of the TLP in m, respectively.

(8) Mooring line stiffness index R_{S}

This index represents the draft of platform, tensile displacement of mooring lines, and pre-tensioning level of mooring lines in the service period for the TLP. Since there are numerous cables whose length is smaller than the water depth mooring the TLP to the ocean floor, the mooring lines generate tensile displacement and are in pre-tension condition to produce the stiffness. A high pre-tensioning level leads to a great mooring line stiffness, which provides good motion control. The stiffness of mooring lines is associated with the pre-tensioning force. It is also related to the quantity and configuration of mooring lines. A much more even mooring lines' configuration leads to a much smaller motion magnitude and increases the stability of the platform. The stiffness of mooring lines is in positive correlation with the pre-tension condition. This index belongs to negative risk: the greater the value, the better.

$$R_{\mathrm{S}}=\frac{d-L-L_{\mathrm{M}}}{d_0-L_0-L_{\mathrm{M}}}, \tag{10}$$

where L is the draft of TLP in m; L_0 is the design draft of TLP in m; L_{M} is the original length of mooring lines without pre-tensioning in m.

(9) Harsh environment index R_{N}

This index represents the risk from a harsh environment for the TLP. The safety of offshore structures is closely related to the ocean environment. A good ocean environment is vital to the safety of the platform. This index belongs to positive risk: the smaller the value, the better.

$$R_{\mathrm{N}}=\frac{N}{N_0}, \tag{11}$$

where N is the number of hurricane days per year; N_0 is the statistic of hurricane days per year in service ocean.

(10) Fire accident index R_{F}

This index represents the influence of a fire accident on safety due to improper flammable gas disposal in the TLP's service period. The flammable gases are by-products when the TLP is working, and how they are disposed of is significant for the TLP's safety. Most of the flammable gases are greenhouse gases that need to be disposed of harmlessly, either stored or burned. The benefits of burning the flammable gas are low cost, simple technology, controllable process, no risk of fire and explosion, but it causes a huge waste of energy. Although it is good to liquefy and store the flammable gas for reuse, the liquefied flammable gas evaporates at all times, and its boil-off gas (BOG) is prone to cause fire and explosion if the disposal is not timely. Therefore, BOG control is of great significance for the safe storage of flammable gases. BOG depends on heat leakage, which is significantly impacted by heat insulating layer thickness, thermal conductivity, and the size of the storage tank (Wu et al., 2017). Heat leakage is almost completely determined by the physical parameters of storage tank, in that the larger the size of storage tank the greater heat leakage, and the higher thermal conductivity the greater heat leakage. BOG is dominated by heat leakage: the greater the heat leakage, the greater the BOG, and the greater the risk of fire and explosion. The index belongs to positive risk: the smaller the value, the better. The smaller risk of fire and explosion, the more stable is the platform.

$$R_{\mathrm{F}}=\frac{D_{\mathrm{L}}\lambda}{\delta}\frac{1}{R_{\mathrm{CE}}}, \tag{12}$$

where D_{L} is the diameter of the storage tank in mm; λ is the heat insulating layer thermal conductivity; δ is the heat insulating layer thickness in mm.

It should be noted that the evaluation risk index group is not fixed, and changes should be made depending on the situation. For example, drilling string failure index, stuck pipe index, wellbore stability index, hook load index, pressure and flow output of mud pump index, well out of control index, blowout index, and so on are other indices that may be considered suitable for the evaluation risk index group of a platform drilling project.

5 Hybrid fuzzy-SPC risk assessment approach of floating attitude for TLP

A TLP's floating attitude risk assessment often includes several mutually restrictive indices and many complex influencing factors. It is needed to reconcile contradictions by weighing the pros and cons, before making a comprehensive evaluation. For one project evaluation, different decision-makers may make different schemes and one decision-maker might obtain several results from different perspectives. In order to obtain a perfect evaluation, generally decision-makers should design many different schemes to conduct a comprehensive analysis. During this process, decision-makers' experience and perspective as well as owner's requirements play a significant role (Wang et al., 2010). However, these experiences, perspectives, and requirements could be ambiguous and difficult to quantify. Thus, it is vital to resolve and quantify those ambiguities in the risk assessment. Fuzzy comprehensive evaluation method is a feasible method to handle such problems.

The methodology of the approach proposed by this paper is: (1) identifying the causes and source of the risk; (2) classifying the causes and source of the risk as risk indices; (3) establishing evaluation risk index group based on risk indices; (4) proposing the hybrid fuzzy-SPC approach (combined with fuzzy comprehensive evaluation method, AHP, and SPC theory) and evaluation scheme (for confidence evaluation) which are suitable for the well-defined risk index group; (5) risk assessment by application of the hybrid fuzzy-SPC model with the well-defined risk index group (Fig. 2). In this paper, section 4 works on the steps (1), (2), and (3) to establish evaluation risk index group; section 5 works on the step (4) to present the novel approach and the evaluation scheme. In step (4), a fuzzy comprehensive evaluation method is applied to handle the ambiguities, combined with AHP and SPC theory to improve the reliability of the risk assessment. Section 6 works on the step (5) to demonstrate an example of how to apply the risk index group and the evaluation scheme with the proposed approach as well as the effectiveness and efficiency of the application.

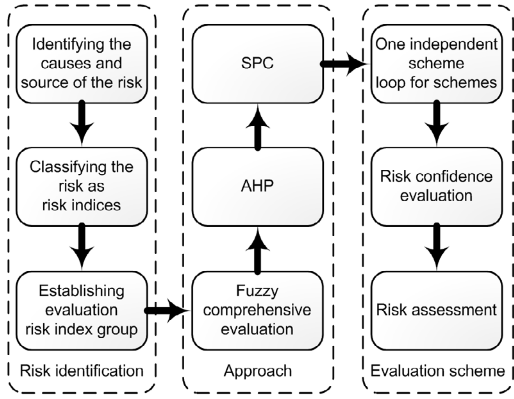

Fig. 2 Risk assessment process (workflow) specimens

5.1 First step: fuzzy comprehensive evaluation method

The purpose of applying the fuzzy comprehensive evaluation method is to handle the 'fuzzification' of indices in assessment. The basic concepts are listed below:

(1) Determine the risk evaluation rank set. The risk evaluation rank set V is made up of several (the number is m) ranks for the nth index.

$$V=(V_1, V_2, \ldots, V_m). \tag{13}$$

(2) Ascertain the fuzzy evaluation index system U_i. Assuming that there are n indices with m risk ranks in the evaluation system, the evaluation index set U_i can be defined as follows:

$$U=(U_1, U_2, \ldots, U_n). \tag{14}$$

(3) Calculate evaluation indices. There is always an expected value M_i and an allowable value m_i for every index of risk rank. Then there is a range of allowable values, denoted as $[m_i, M_i]$. Define a corresponding optimal value fuzzy set function A_i in the interval, which derives from the fuzzy evaluation index system U_i. That is,

$$A_i=\int \frac{\mu_{A_i}(u_i)}{u_i}, \quad u_i \in [m_i, M_i], \tag{15}$$

where $\mu_{A_i}(u_i)$ is the membership function for u_i. The fuzzy memberships can be calculated as falling in the range from 0 to 1, which represents the satisfactory degree of the corresponding evaluation index and indicates the uncertainty or imprecise information of the system.

In the situation that the satisfactory degree monotonously increases as the evaluation index value increases, the form of $\mu_{A_i}(u_i)$ is as follows:

$$\mu_{A_i}(u_i)=\begin{cases}0, & u_i \le m_i, \\ L_i(u_i), & m_i < u_i < M_i, \\ 1, & u_i \ge M_i.\end{cases} \tag{16}$$

In the situation that the satisfactory degree monotonously decreases as the evaluation index value increases, the form of $\mu_{A_i}(u_i)$ is as follows:

$$\mu_{A_i}(u_i)=\begin{cases}1, & u_i \le m_i, \\ L_i(u_i), & m_i < u_i < M_i, \\ 0, & u_i \ge M_i.\end{cases} \tag{17}$$

Based on the evaluation index system and evaluating rules, the fuzzy relationship matrix is obtained by ascertaining the evaluation index value, and it is calculated using a membership function. A judgment matrix is formed by evaluating every risk rank and evaluation index with a nine-point scale.

$$\boldsymbol{R}=\left(r_{ij}\right)_{n\times m}, \tag{18}$$

where r_{ij} represents the fuzzy membership of the ith evaluation index belonging to the jth risk rank. Each row is an evaluation result of risk ranks for the ith evaluation index, as well as a grade for a uniform standard; each column is the evaluation result of all evaluation indices for the jth risk rank. Therefore, this matrix is of a single-factor evaluation form.

(4) Comprehensive evaluation. As mentioned earlier, risk evaluation relates to several mutually restrictive indices and many complex influencing factors. Therefore, it is necessary to take a multi-index comprehensive evaluation after the single index evaluation for all risk ranks. The concept of importance is introduced. The importance is denoted as ω_i, i=1, 2, …, n. It characterizes the importance level of evaluation indices for risk ranks. It is a fuzzy subset for the evaluation index set. That is,

$$\boldsymbol{W}=\left(\frac{\omega_1}{u_1}, \frac{\omega_2}{u_2}, \cdots, \frac{\omega_n}{u_n}\right). \tag{19}$$

To normalize ω_i, define $\alpha_i=\dfrac{\omega_i}{W}$, where $W=\sum_{i=1}^{n}\omega_i$. α_i is the weight (importance level) of the ith index for evaluation, i=1, 2, …, n. $\boldsymbol{A}$=(α_1, α_2, …, α_n) is a weight vector, determined by the importance level and membership function.

After the establishment of the satisfactory degree and importance level of evaluation indices, the problem of comprehensive evaluation is boiled down to

$$\boldsymbol{B}=\boldsymbol{A}\circ\boldsymbol{R}=\left(\frac{b_1}{v_1}, \frac{b_2}{v_2}, \cdots, \frac{b_m}{v_m}\right), \tag{20}$$

where $\circ$ is a fuzzy composition operator. $b_j=\alpha_1 r_{1j}+\alpha_2 r_{2j}+\alpha_3 r_{3j}+\ldots+\alpha_n r_{nj}$, for j=1, 2, 3, …, m.

The fuzzy operator is defined as: $M(\bullet,\oplus)$, $b_j=\min\left(1, \sum_{i=1}^{n}\alpha_i\times r_{ij}\right), b_j\in\boldsymbol{B}$.

Actually b_j is the fuzzy membership of comprehensive evaluation belonging to the jth risk rank, j=1, 2, 3, …, m. Based on the value of b_j, the comprehensive evaluation grade is determined.

Using the fuzzy comprehensive evaluation method, a set of grade alternatives or linguistic evaluations and scores should be established for risk grades in order to determine a standard E. Determine the r levels set of grade alternatives E={e_1, e_2, e_3, …, e_r}, where r is the number of alternatives. For example, e_1=very low, e_2=low, e_3=moderate, e_4=high, and e_5=very high. Grades will be given for each alternative. In this study, establishment of a five grades evaluation criterion is used to calculate the risk grade of each risk. Grade criteria are defined as a set E, E={1, 2, 3, 4, 5}, where 1=very low, 2=low, 3=moderate, 4=high, and 5=very high (for more details about the procedures, please refer to Xu et al. (2010), Liu et al. (2013), and Chen et al. (2015)).

For each criterion, an evaluation is a fuzzy subset of a grade set whose membership function can be established by the risk evaluation group. For example, it may be that the survey results based on the value of risk indices on the probability of wave height index indicate that 0% of the experts opine the probability of occurrence as very low, 10% opine as low, 30% opine as moderate, 50% opine as high, and 10% opine as very high. Further explanation of the above results: statistics grade is obtained because these risk indices are graded by experts. Consequently, the statistics grade which is summarized from all experts' grade becomes the statistical value of the probability of risk occurrence. For the evaluation of all criteria, the grade of each criterion is a fuzzy subset of the grade set as well as it is a membership function vector of itself. It is a fuzzy set primarily because of the absence of an accurate standard. The membership function of wave height index is given by

$$\begin{aligned} f_1 &= \frac{0.00}{\text{very low}} + \frac{0.10}{\text{low}} \\ &+ \frac{0.30}{\text{moderate}} + \frac{0.50}{\text{high}} + \frac{0.10}{\text{very high}} \\ &= \frac{0.00}{1} + \frac{0.10}{2} + \frac{0.30}{3} + \frac{0.50}{4} + \frac{0.10}{5}. \end{aligned} \tag{21}$$

f_1 can also be written as (0.00, 0.10, 0.30, 0.50, 0.10). All the evaluations of risk indices form a fuzzy evaluation matrix $\boldsymbol{R}=(r_{ij})_{n\times m}$, where r_{ij} is the degree to which alternative e_r satisfies the criterion f_i.

5.2 Second step: analytic hierarchy process in fuzzy evaluation

The purpose of applying AHP is to determine the weight of a criterion with a comparable uniformity. In the process of fuzzy evaluation, AHP is needed for the probability of risk occurrence. The evaluation criterion for each risk is established to evaluate each risk index with probability, severity, non-detectability, and worsening factors. In this way, the risk evaluated in the same evaluation criterion is comparable.

Based on the four evaluation criteria, a structure of AHP (Fig. 3) can be established (Saaty and Vargas, 2006).

Pairwise comparison matrices are conducted using fundamental scales 1–9 with probability, severity, non-detectability, and worsening factors formed by experts and engineers (Saaty, 1980). The judgment matrix can be formed by pairwise comparisons with the relative importance of the overall risks.

In this study, probability, severity, non-detectability, and worsening factors are represented by J_1, J_2, J_3, J_4 (Liu et al., 2013). The judgment matrix is given in Table 2. The AHP relative importance scale is shown in Table 3.

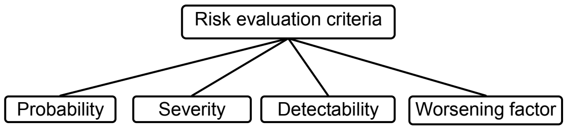

Fig. 3 Hierarchy structure of risk evaluation

Table 2 Judgment matrix

	J_1	J_2	J_3	J_4
J_1	1	1/4	1/2	1/4
J_2	4	1	2	1
J_3	2	1/2	1	1/2
J_4	4	1	2	1

J_1: probability; J_2: severity; J_3: non-detectability; J_4: worsening factors

Table 3 Analytic hierarchy process (AHP) relative importance scale

Intensity of importance	Explanation
1	Two factors contribute equally to the objective
3	Experience and judgement slightly favor one over the other
5	Experience and judgement strongly favor one over the other
7	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in practice
9	Evidence favoring one over the other is of the highest possible validity
2, 4, 6, 8	Intermediate values between two factors, when compromise is needed

5.3 Third step: statistical process control for confidence control limits in fuzzy evaluation

The purpose to apply SPC is to handle the assignable variation in assessment. For the same evaluation, different decision-makers may make different schemes and one decision-maker might obtain several results from different perspectives. In simple terms, subjective factors have a great impact on the results. Therefore, the probability of risk occurrence proposed by different experts and engineers should be subjected to prudent analysis for risk evaluation. In order to obtain a perfect evaluation, we need to use SPC theory and confidence analysis to confirm the confidence level.

5.3.1 Statistical process control theory

SPC is an analytical decision-making method based on the mathematical statistical characteristics of fluctuation in a process to monitor and control through observing common and assignable variation, warning of unusual trends, eliminating assignable causes, and recovering the stability of the process. The variation in the range of control limits (common variation) is a natural attribute of the process and is expected as part of the process. If the variation falls outside of the range of control limits (assignable variation), it indicates that there might be assignable reasons in the system. If the process is under control, the statistical characteristics of fluctuation in the process have a stable stochastic distribution. Otherwise it will have an unstable stochastic distribution. SPC control charts, which are a useful graphical tool, use statistical "discovering unusual" as a tool in the control process to monitor common and assignable variation. Control limits are established by valid data, called upper control limit (UCL), lower control limit (LCL), and center line (CL). Generally, UCL is CL+3σ, and LCL is CL−3σ, where σ is the standard deviation. Data should not fall outside of control limits if there is not any assignable cause in the process (Alwan and Roberts, 1988; MacGregor and Kourti, 1995; Montgomery, 2009).

5.3.2 Confidence evaluation

To take the advantage of reverse SPC theory, the concept of confidence level $1-\alpha$ and confidence interval are introduced (Teng and Feng, 2005). By assuming the risk assessment is under control (falling in between UCL and LCL) (if not, the risk assessment is unacceptable because the assignable cause has a great impact on the risk assessment), the risk level is within the range of control limits with a confidence level of $1-\alpha$ for risk center line R, where α is the significance level. Then the acceptable risk interval can be calculated based on the confidence evaluation.

The risk results calculated by all evaluation schemes are included in the total sample. Each result of risk evaluation schemes is independent and a simple random sample of the total sample. For the given $\alpha\in(0, 1)$, if risk values T_1 and T_2 meet the condition:

$$P\left(T_1 \le R \le T_2\right) = 1-\alpha. \tag{22}$$

Take the situation that the risk interval $[T_1, T_2]$ is the confidence interval with a confidence level of $1-\alpha$ for risk value R. It is believed that the risk is probable to occur in this risk confidence interval. T_1 and T_2 are LCL and UCL, respectively.

According to the central limit theorem, for any overall sample

$$\frac{\bar{X}-\mathrm{EX}}{\sqrt{\mathrm{DX}}\big/\sqrt{s}} \xrightarrow{F} N(0,1), \tag{23}$$

where $\bar{X}$ is the variable, EX is the expected value, DX is the variance, and s is the sample size.

For the confidence level of $1-\alpha$, the form of confidence interval of risk value R is:

$$\left[\bar{X}-Z_{\alpha/2}\sqrt{\mathrm{DX}}\big/\sqrt{s},\ \bar{X}+Z_{\alpha/2}\sqrt{\mathrm{DX}}\big/\sqrt{s}\right]. \tag{24}$$

"Small probability event" usually refers to the probability of an event occurring being less than 5%. It is believed that a small probability event is almost impossible to occur.

The 3σ principle is used to analyze the credibility with $P(|X-\mu|<3\sigma)=0.9974$ (99.74%), where μ is the expectation. Consequently, the result is credible in the range of control limits with a confidence level of 0.95.

For the pros of the proposed approach, this hybrid fuzzy-SPC risk assessment approach could assess the risk as a risk confidence interval with the required confidence level. By combining fuzzy comprehensive evaluation method, AHP, and SPC principles, the impact of uncertainties and subjectivities is reduced, achieving better results than only utilizing a single method. In addition, the risk assessment could be made more reliable if the risk index group can cover all the risk factors based on the requirement. It is less complicated to determine the risk level and identify the most significant risk index. However, the cons of the approach are inevitable. The approach depends on the statistics grade of the experts. This is a statistic and needs a lot of experts to grade, to get a fuzzy subset of the grade set. In addition, one statistics grade only fits one independent evaluation scheme, and that leads to the fact that a statistics grade is not universally applicable to all schemes.

6 Examples

The risk assessment of Liu Hua 16-2 TLP (weights and loads approximate 43188 t, more detail in Fig. 4) is taken as an example to illustrate reasonability and universality of the approach (an Excel procedure has been established). For simplicity, wave height index, mooring line index, crew operating equipment index, service life index, combined load index of wind, wave, and current as risk indices are selected for evaluation. Other indices are not included in this case. Ten independent risk evaluation schemes are built to derive a risk confidence interval.

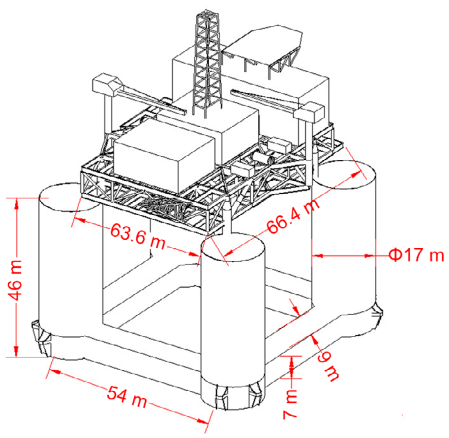

Fig. 4 Detail of Liu Hua 16-2 TLP

6.1 Risk evaluation for one independent scheme

The weight of each criterion is calculated as (0.10, 0.36, 0.18, 0.36).

For one independent scheme, the distribution of risk grades is shown in Table 4. For a more precise risk assessment, ten independent evaluation schemes will be proposed by experts and engineers in the next section.

6.1.1 Risk indices calculation

The results of five risk indices are summarized in Table 5.

In order to evaluate objectively, a pairwise comparison matrix is established by a certain number of experts evaluating the relative importance degree of risk indices. The final result is determined as follows:

$$\boldsymbol{A}=\begin{bmatrix} 1 & 3 & 5 & 2 & \frac{1}{2} \\ \frac{1}{3} & 1 & 2 & \frac{1}{2} & \frac{1}{5} \\ \frac{1}{5} & \frac{1}{2} & 1 & \frac{1}{4} & \frac{1}{6} \\ \frac{1}{2} & 2 & 4 & 1 & \frac{1}{4} \\ 2 & 5 & 6 & 4 & 1 \end{bmatrix}.$$

Table 4 Distribution of risk grades

Risk factor	Risk grade					
	Standard	Very low	Low	Moderate	High	Very high
Wave height index	J_1	0.0	0.1	0.3	0.5	0.1
	J_2	0.2	0.2	0.2	0.2	0.2
	J_3	0.0	0.0	0.3	0.3	0.4
	J_4	0.2	0.2	0.2	0.2	0.2
Mooring line index	J_1	0.0	0.3	0.3	0.3	0.1
	J_2	0.2	0.2	0.2	0.2	0.2
	J_3	0.3	0.3	0.3	0.1	0.0
	J_4	0.1	0.2	0.4	0.2	0.1
Crew operating equipment index	J_1	0.1	0.2	0.4	0.2	0.1
	J_2	0.2	0.2	0.2	0.2	0.2
	J_3	0.0	0.3	0.4	0.3	0.0
	J_4	0.4	0.4	0.1	0.1	0.0
Service life index	J_1	0.1	0.2	0.4	0.2	0.1
	J_2	0.0	0.0	0.3	0.3	0.4
	J_3	0.3	0.3	0.3	0.1	0.0
	J_4	0.2	0.2	0.2	0.2	0.2
Combined load index of wind, wave, and current	J_1	0.0	0.0	0.1	0.8	0.1
	J_2	0.0	0.1	0.4	0.4	0.1
	J_3	0.0	0.0	0.1	0.4	0.5
	J_4	0.0	0.1	0.4	0.4	0.1

J_1: probability; J_2: severity; J_3: non-detectability; J_4: worsening factors

Table 5 Results summary of risk factors

Risk factor	Membership function	Risk index	Risk ranking
Wave height index	(0.144, 0.154, 0.228, 0.248, 0.226)	3.258	2
Mooring line index	(0.162, 0.228, 0.300, 0.192, 0.118)	2.876	4
Crew operating equipment index	(0.226, 0.290, 0.220, 0.182, 0.082)	2.604	5
Service life index	(0.136, 0.146, 0.274, 0.218, 0.226)	3.252	3
Combined load index of wind, wave and current	(0.000, 0.072, 0.316, 0.440, 0.172)	3.712	1

6.1.2 Consistency test

To assure a certain quality level of a decision, the consistency of an evaluation should be analyzed. CI is the consistence index for a comparison matrix. CI is defined as CI=($\lambda_{max}-n$)/($n-1$), where λ_{max} is the largest eigenvalue of the comparison matrix, and n is the dimension of the matrix. RI is a random index that depends on the size of matrix, n. The consistency ratio (CR) is defined as a ratio between the consistency of a given evaluation matrix and consistency of a random matrix. The definition is CR=CI/RI. If the CR of a comparison matrix is equal or less than 0.1, it can be acceptable. When the CR is unacceptable, the decision-maker is encouraged to repeat the pairwise comparisons (Chen et al., 2015). Consistency investigation: $\lambda_{max(\boldsymbol{A})}$=5.0842, CI=0.0211, RI=1.12, CR=0.0188<0.1.

Therefore, the consistency of $\boldsymbol{A}$ is acceptable.

6.1.3 Fuzzy evaluation

By calculation, the weight vector of $\boldsymbol{A}$ is $\boldsymbol{\omega}(\boldsymbol{A})$=(0.2650, 0.0929, 0.0488, 0.1786, 0.4147).

The results of fuzzy evaluation of the overall risk is calculated by a composite weight vector and fuzzy evaluation matrix. The final result is obtained by a pairwise comparison matrix multiplying the membership function.

$$\boldsymbol{D}_A = \boldsymbol{\omega}(\boldsymbol{A}) \circ \boldsymbol{R}_A = \left(0.0885,\ 0.1321,\ 0.2790,\ 0.3138,\ 0.1865\right), \tag{25}$$

where $\boldsymbol{D}_A$ is membership function of overall risk.

The formula to calculate the overall risk index (R.I.) value is $\text{R.I.} = \sum_{k=1}^{n} d_k \times e_k$, where d_k are elements of $\boldsymbol{D}_A$, and e_k are elements of E.

6.2 Risk confidence evaluation based on ten independent schemes

6.2.1 Risk distributions of ten independent schemes

Independent evaluation schemes are repeated as shown in section 6.1, and their ten risk distributions are summarized in Table 6. Additional calculation can be done to increase the accuracy according to the demand of the project. For simplicity, the number of risk evaluation schemes is 10 in this study, but it can also be 100 or 1000 according to the actual conditions. No fewer than 10 are acceptable.

Table 6 Tension leg platform risk index

Scheme	Membership function	Risk index
1	(0.0094, 0.0251, 0.1870, 0.4145, 0.3696)	4.127
2	(0.0095, 0.0539, 0.2989, 0.4271, 0.2150)	3.798
3	(0.0093, 0.0776, 0.3214, 0.3942, 0.1975)	3.693
4	(0.0085, 0.0801, 0.3249, 0.4067, 0.1798)	3.669
5	(0.0018, 0.0743, 0.3130, 0.4584, 0.1526)	3.686
6	(0.0300, 0.0646, 0.2884, 0.4685, 0.1485)	3.641
7	(0.0396, 0.0930, 0.2675, 0.4376, 0.1874)	3.716
8	(0.1036, 0.1771, 0.2685, 0.3028, 0.1480)	3.215
9	(0.1391, 0.1917, 0.2742, 0.2465, 0.1485)	3.074
10	(0.0885, 0.1321, 0.2790, 0.3138, 0.1865)	3.378

6.2.2 Results and discussion

The No. 10 scheme is taken as an example to demonstrate the results, although it is not intended to represent the actual case. The overall risk value of the TLP floating attitude is 3.378, which can be considered as a moderate level of risk with respect to five level evaluation criteria. Therefore, the risk level of the project can be construed as a "moderate" level with this evaluation scheme. Moreover, among various risks, "combined load index of wind, wave, and current" is the most dangerous risk, with risk index 3.712; "wave height index" is the second, with a risk index of 3.258. It means that those risk indices are more likely to happen and might threaten the floating attitude. At least one risk index will happen with the probability not greater than 3.378/5=67.56%. In other words, there is no more than 67.56% probability that floating attitude stability disappears due to the risk indices as mentioned. It should be noted that this risk value is one result of the various evaluation schemes, and cannot represent the final risk level.

The risk result of ten independent schemes is independent and a simple random sample of the total sample. Risk interval [T_1, T_2] is the confidence interval with confidence level of $1-\alpha$ for risk value R:

$$\left[\bar{X} - Z_{\alpha/2}\sqrt{\mathrm{DX}}\big/\sqrt{n},\ \bar{X} + Z_{\alpha/2}\sqrt{\mathrm{DX}}\big/\sqrt{n}\right].$$

It is credible in the range of confidence interval [3.4212, 3.7777] (control limits) with 0.95 confidence level. In the five grade evaluation criteria, the result is between moderate and high risk levels. It means that these risk indices are more likely to threaten attitude. At least one risk index will happen with the probability not greater than 68.42%–75.55%. In other words, there is no more than 68.42%–75.55% probability that stability control disappears due to the most dangerous risk indices. Safety measures are needed to implement around known risks.

In 10 evaluation schemes, the indices that affect the risk evaluation of floating attitude such as "combined load index of wind, wave, and current" and "wave height index" are labeled 5 times and 3 times among the most dangerous indices. Assessment results are consistent with objective analysis because the same indices become the most dangerous indices in multiple independent evaluation schemes. In designing a tension leg mooring system and hull below topsides, it is necessary to pay more attention to these dangerous risk indices and take various factors into account, such as increasing the safety factor to improve safety and reliability.

7 Conclusions

This paper proposes a risk assessment approach for TLP floating attitude, named hybrid fuzzy-SPC model, that provides more precise estimation than other commonly used methods. The hybrid fuzzy-SPC model is designed to follow risk source identification and establishment of risk index groups. It consists of three principal methods: fuzzy comprehensive evaluation, AHP, and SPC theory. In comparison to applying only one of the three, hybrid fuzzy-SPC model usually results in reduction in uncertainties and subjectivities. In order to take advantage of reverse SPC theory, by assuming the risk assessment is under control, each result of risk evaluation schemes is independent and a simple random sample of the total sample. The fuzzy comprehensive evaluation method and AHP are used to obtain several independent risk evaluation scheme results. Then, based on the SPC theory, a practitioner is able to derive a confidence interval using the central limit theorem to get the risk control limits with the required confidence level. Conclusions are as follows:

(1) The evaluation risk index group is flexible and its changes can be made consciously according to the situation. For various purposes, the risk index groups for different project needs are established to get diversified evaluation results. In fact, the risk index group is more than that, and should be adjusted according to the emphasis of the project.

(2) The number of risk evaluation schemes depends on the demands of the project. No fewer than 10 are acceptable.

(3) It is less complicated to determine the risk levels and identify the most threatening risk index, because the confidence risk evaluation reflects the real magnitude of risk with a high confidence level. With known center lines, the risk can be mitigated, with safety measures implemented around known risks.

The approach's methodology is assessing the risk by applying the hybrid fuzzy-SPC model with a well-defined risk index group. The proposed model and risk indices can be applied in the field of offshore engineering separately or conjointly. The risk index group is flexible and its changes can be made consciously according to the situation, but the well-defined group is necessary to assess the risk by application of the hybrid fuzzy-SPC model, because it is the important input of hybrid fuzzy-SPC model. The approach is universal and can be applied in most operational situations of engineering projects with a well-defined risk index group. Future work should focus on how to reduce the workload (fewer schemes) but giving as good results as are currently available with SPC applied.

Contributors

Hao WU wrote the first draft of the manuscript. Hao WU and Yan LIN revised and edited the final version.

Conflict of interest

Hao WU and Yan LIN declare that they have no conflict of interest.

References

Alwan LC, Roberts HV, 1988. Time-series modeling for statistical process control. *Journal of Business & Economic Statistics*, 6(1):87-95. https://doi.org/10.1080/07350015.1988.10509640

Benassai G, Campanile A, Piscopo V, et al., 2014. Ultimate and accidental limit state design for mooring systems of floating offshore wind turbines. *Ocean Engineering*, 92:64-74. https://doi.org/10.1016/j.oceaneng.2014.09.036

Carr V, Tah JHM, 2001. A fuzzy approach to construction project risk assessment and analysis: construction project risk management system. *Advances in Engineering Software*, 32(10-11):847-857.
https://doi.org/10.1016/s0965-9978(01)00036-9

CCS (China Classification Society), OCIMF (Oil Companies International Marine Forum), 2015. Effective Mooring, 3rd Edition. CCS and OCIMF.

Chatjigeorgiou IK, Mavrakos SA, 2002. An investigation of the non-linear transverse vibrations of parametrically excited vertical marine risers and cables under tension. Proceedings of the ASME 21st International Conference on Offshore Mechanics and Arctic Engineering, p.347-358.
https://doi.org/10.1115/OMAE2002-28170

Chen JF, Hsieh HN, Do QH, 2015. Evaluating teaching performance based on fuzzy AHP and comprehensive evaluation approach. *Applied Soft Computing*, 28:100-108.
https://doi.org/10.1016/j.asoc.2014.11.050

Chen JJ, Zhou L, 2014. Risks and inspection of FPSO single point mooring system. *Petroleum Engineering Construction*, 40(4):24-28 (in Chinese).
https://doi.org/10.3969/j.issn.1001-2206.2014.04.006

Coelho DK, Roisenberg M, de Freitas Filho PJ, et al., 2005. Risk assessment of drilling and completion operations in petroleum wells using a Monte Carlo and a neural network approach. Proceedings of the 37th Conference on Winter Simulation, p.1892-1897.
https://doi.org/10.1109/WSC.2005.1574466

Dean RG, Dalrymple RA, 1991. Water Wave Mechanics for Engineers and Scientists. World Scientific, Singapore, p.96-98.

Fattahi R, Khalilzadeh M, 2018. Risk evaluation using a novel hybrid method based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment. *Safety Science*, 102:290-300.
https://doi.org/10.1016/j.ssci.2017.10.018

Flocard F, Finnigan TD, 2010. Laboratory experiments on the power capture of pitching vertical cylinders in waves. *Ocean Engineering*, 37(11-12):989-997.
https://doi.org/10.1016/j.oceaneng.2010.03.011

Hu Y, Hu ZJ, Liu YD, et al., 2012. Analysis of the large LNG ships moored against a quay based on AQWA. *Ship Science and Technology*, 34(2):70-73 (in Chinese).
https://doi.org/10.3404/j.issn.1672-7649.2012.02.014

ISO (International Organization for Standardization), 2009a. Risk Management—Principles and Guidelines, ISO 31000:2009. ISO.

ISO (International Organization for Standardization), 2009b. Risk Management—Risk Assessment Techniques, ISO/IEC 31010:2009. ISO.

Jin YL, Jang BS, 2015. Probabilistic fire risk analysis and structural safety assessment of FPSO topside module. *Ocean Engineering*, 104:725-737.
https://doi.org/10.1016/j.oceaneng.2015.04.019

Jing Y, 2007. The comparison of two different mooring systems. *Shipbuilding of China*, 48(S1):660-664 (in Chinese).

Kurian VJ, Gasim MA, Narayan SP, et al., 2008. Parametric study of TLPs subjected to random waves. Proceedings of International Conference on Construction and Building Technology, p.213-222.

Liu JL, 2013. Study on Risk Analysis of Large Engineering Project Method Based on Fuzzy Statistical Decision Theory. PhD Thesis, Jilin University, Changchun, China (in Chinese).

Liu JL, Li QX, Wang YH, 2013. Risk analysis in ultra deep scientific drilling project—a fuzzy synthetic evaluation approach. *International Journal of Project Management*, 31(3):449-458.
https://doi.org/10.1016/j.ijproman.2012.09.015

MacGregor JF, Kourti T, 1995. Statistical process control of multivariate processes. *Control Engineering Practice*, 3(3):403-414.
https://doi.org/10.1016/0967-0661(95)00014-l

Mentes A, Helvacioglu IH, 2011. An application of fuzzy fault tree analysis for spread mooring systems. *Ocean Engineering*, 38(2-3):285-294.
https://doi.org/10.1016/j.oceaneng.2010.11.003

Montgomery DC, 2009. Introduction to Statistical Quality Control, 6th Edition. Wiley, New York, USA.

Nieto-Morote A, Ruz-Vila F, 2011. A fuzzy approach to construction project risk assessment. *International Journal of Project Management*, 29(2):220-231.
https://doi.org/10.1016/j.ijproman.2010.02.002

Osborn RW, Millwater HR, 2005. Application of probabilistic sensitivities in probabilistic fatigue analysis of gas turbine engine disks. Proceedings of the 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Article No. 2147.

Saaty TL, 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York, USA.

Saaty TL, Vargas LG, 2006. Decision Making with the Analytic Network Process: Economic, Political, Social and Technological Applications with Benefits, Opportunities, Costs and Risks. Springer, Boston, USA.
https://doi.org/10.1007/0-387-33987-6

Sadiq R, Husain T, Veitch B, et al., 2004. Risk-based decision-making for drilling waste discharges using a fuzzy synthetic evaluation technique. *Ocean Engineering*, 31(16):1929-1953.
https://doi.org/10.1016/j.oceaneng.2004.05.001

Simos AM, Pesce CP, 1997. Mathieu stability in the dynamics of TLP's tethers considering variable tension along the length. *In*: Carneiro FLLB, Ferrante AJ, Batista RC, et al. (Eds.), Offshore Engineering. WIT Press, Ashurst, UK.

Sohn H, Czarnecki JA, Farrar CR, 2000. Structural health monitoring using statistical process control. *Journal of Structural Engineering*, 126(11):1356-1363.
https://doi.org/10.1061/(asce)0733-9445(2000)126:11(1356)

Taroun A, Yang JB, Lowe D, 2011. Construction risk modelling and assessment: insights from a literature review. *The Built & Human Environment Review*, 4(S1): 87-97.

Teng SZ, Feng JH, 2005. Mathematical Statistics, 4th Edition. Dalian University of Technology Press, Dalian, China, p.81-99 (in Chinese).

Wang Y, Li Y, Liu W, et al., 2015. Assessing operational ocean observing equipment (OOOE) based on the fuzzy comprehensive evaluation method. *Ocean Engineering*, 107:54-59. https://doi.org/10.1016/j.oceaneng.2015.07.032

Wang YL, Chen M, Ji ZS, et al., 2007. The evaluation criteria system and evaluation method for self elevating drilling unit. *Journal of Shanghai Jiaotong University*, 41(9): 1445-1448 (in Chinese). https://doi.org/10.3321/j.issn:1006-2467.2007.09.012

Wang YL, Ji ZS, Lin Y, 2010. The advanced grade evaluation of self-elevating drilling unit. *Journal of Shanghai Jiaotong University*, 44(6):755-757 (in Chinese). https://doi.org/10.16183/j.cnki.jsjtu.2010.06.008

Wu H, Lin Y, Ye C, et al., 2017. Simplified algorithm of evaporation rate for 1.5 m^3 independent and C-type LNG storage tank. *Journal of Dalian University of Technology*, 57(1):37-45 (in Chinese). https://doi.org/10.7511/dllgxb201701006

Xu YL, Yeung JFY, Chan APC, et al., 2010. Developing a risk assessment model for PPP projects in China—a fuzzy synthetic evaluation approach. *Automation in Construction*, 19(7):929-943. https://doi.org/10.1016/j.autcon.2010.06.006

Yan GW, Ou JP, 2010. Dynamic response analysis on different types of TLPs. Proceedings of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering, p.161-168. https://doi.org/10.1115/OMAE2010-20173

Yang G, Zhang JY, Wang N, et al., 2015. Introduction of the risk assessment of in-service soft yoke mooring system. *Science and Technology Innovation Herald*, 12(6):242-245 (in Chinese). https://doi.org/10.16660/j.cnki.1674-098x.2015.06.049

Yang ZL, Wang J, 2015. Use of fuzzy risk assessment in FMEA of offshore engineering systems. *Ocean Engineering*, 95:195-204. https://doi.org/10.1016/j.oceaneng.2014.11.037

Zeng JH, An M, Smith NJ, 2007. Application of a fuzzy based decision making methodology to construction project risk assessment. *International Journal of Project Management*, 25(6):589-600. https://doi.org/10.1016/j.ijproman.2007.02.006

Zhang Y, 2011. Research on Buckling Assessment Method of Hull Structure with Corrosion Damnification. PhD Thesis, Dalian University of Technology, Dalian, China (in Chinese).

中文概要

题　目：基于模糊统计过程控制模型的张力腿平台漂浮姿态的风险评估

目　的：张力腿平台在海上服役时由于振动和系泊问题有漂浮姿态丧失的风险。平台漂浮姿态丧失后会影响作业稳定性和服役安全性。本文旨在对平台漂浮姿态丧失进行风险分析，评估总体的风险等级，识别最具威胁的风险因素，提前采取有效措施，并及时向设计、建造和运营提供反馈意见，保证平台运行安全。

创新点：1. 在模糊理论的基础上融合统计过程控制理论和层次分析法，形成模糊统计过程控制评估模型；2. 建立适用于评估目标的风险评估指标体系，并作为参数输入该风险评估模型，最终获得风险置信区间。

方　法：1. 识别影响漂浮姿态的风险因素并归纳分解，建立风险评估指标体系，并将其作为模糊统计过程控制评估模型的输入参数；2. 将应用模糊理论和层次分析法得到的单一独立评价方案的风险结果视为风险的总体随机样本，并利用中心极限定理对风险评估结果进行置信度评价，以获得最终的风险置信区间。

结　论：1. 三种方法的融合使得不确定性和主观性对风险评估的影响大幅减少，结果好于单独用其中任何一种评估方法。2. 风险评价指标体系是柔性的，需要随着实际情况做出适当的调整。3. 独立风险评价方案的数量依赖于项目的需求，高精度的评估结果需要大量的独立评价方案做底层支撑；独立评价方案的数量不能小于 10。4. 风险评价指标体系可以不同，但是风险评估方法具有普适性。

关键词：张力腿平台；风险评估；漂浮姿态；混合模型；模糊统计过程控制