Arabian Journal for Science and Engineering (2018) 43:2659–2672
https://doi.org/10.1007/s13369-017-3004-2

RESEARCH ARTICLE - PETROLEUM ENGINEERING

Risk Assessment Method of Subsea Wellhead Instability in Consideration of Uncertain Factors in Deepwater Drilling

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Received: 3 January 2017 / Accepted: 25 October 2017 / Published online: 13 December 2017

Abstract

In deepwater drilling, the subsea wellhead is in a complicated stress state and carries the risk of instability. The mechanical stability of subsea wellhead has gradually become one of the key factors in the design and construction of deepwater drilling. In this paper, through the analysis of stress and deformation of subsea wellhead system in deepwater drilling, the characteristic parameters that characterize the mechanical stability of subsea wellhead were determined. On this basis, the influence of different factors on characteristic parameters was analyzed based on dimensionless processing and sensitivity analysis. Factors that were more sensitive and had greater impact on the wellhead mechanical stability of the instance well were screened. Aiming at the problem of greater uncertainty of resistance coefficient, the risk assessment method of subsea wellhead instability considering of uncertain factors was established. Using this method, the wellhead instability risks could be quantitatively evaluated in the drilling process, construction parameters and monitoring values of environmental loads which meet the wellhead safety requirements that could also be proposed. Example shows that: according to the selected parameters such as center value of drag coefficient $\mu = 0.8$, fluctuation coefficient of drag coefficient $\sigma = 0.05$, safety limit of subsea wellhead displacement $S_{\mathrm{wm}} = 0.37\,\mathrm{m}$, and safety limit of subsea wellhead deflection angle $\theta_{\mathrm{wm}} = 3.1°$, there was 24% probability of occurrence of wellhead instability for the target well. Meanwhile, the platform drift S_{w} should be < 43 m, and the maximum marine current velocity u_{w} should be $< 1.188\ \mathrm{m\ s^{-1}}$.

Keywords Deepwater drilling · Subsea wellhead mechanical stability · Wellhead instability · Uncertainty analysis · Risk assessment

1 Introduction

The biggest difference between deepwater drilling and shallow drilling or land drilling is the water depth, which requires a long riser to ensure the drilling operations. Meanwhile, the mechanical properties of seabed shallow soil are also changed with the increase in water depth [1]. Under the influence of drilling ship drift, marine current shock and other factors, the subsea wellhead is in a complicated stress state, and the risk of wellhead instability exists [2]. Therefore, the mechanical stability of subsea wellhead has gradually become one of the key factors in the design and construction of deepwater drilling.

In recent years, scholars have made a deep research on the mechanical behavior of subsea wellhead system in deepwater drilling. As early as in 1980s, Stahl et al. [3] did preliminary research on the stability of subsea wellhead under shallow water drilling. In 1990s, King et al. [4] proposed a finite element method for stress coupling analysis of subsea wellhead. With the development of deepwater drilling, the stability and fatigue life of subsea wellhead attracted more and more attention. Scholars began to study the problems of coupling analysis of the riser–subsea wellhead system and the fatigue life monitoring system of subsea wellhead [5–12,14] and tried to make breakthroughs in the related field. These studies generally include: the dynamic response of deepwater drilling riser [13], the coupling stress analysis of

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riser–wellhead system [13–16], real time and ultimate bearing capacity of the conductor [17], the fatigue life prediction of the subsea wellhead [18], and the mechanical stability of the subsea wellhead [16]. These studies have been gradually perfected in the computational models, which considered the influence of environmental factors and actual working conditions. It provided theoretical basis and technical support for the issue of subsea wellhead stability in deepwater drilling. However, few of the existing models had considered the risks caused by the uncertainty of complex environmental loads under deepwater conditions. And some of the sensitive parameters were still calculated as fixed value, which reduced the reliability of the calculation models. Meanwhile, for the deepwater drilling, there was no relevant report on the quantitative risk analysis of subsea wellhead instability. Therefore, it is necessary to analyze the influence parameters of subsea wellhead mechanical stability, which are not only sensitive but also uncertain, on the basis of previous studies. And the risk assessment method of subsea wellhead instability considering uncertain factors in deepwater drilling should be established. It could provide support for the subsea wellhead design, construction and risk mitigation in deepwater drilling.

2 Calculation Model of Mechanical Stability of Subsea Wellhead System

In order to study the mechanical stability of subsea wellhead, factors such as environmental loads, drilling ship drift, riser top tension, subsea shallow soil properties, and conductor setting depth should be comprehensively considered. Therefore, the riser, subsea wellhead, and conductor need to be seen as a system for the mechanical analysis. The coupling mechanics analysis model of riser–subsea wellhead–conductor has been developed and perfected for many years, and its computational accuracy could meet the needs of the project. Through investigation, a coupling model with high universality [16] was adopted to analyze the stress situation of the deepwater subsea wellhead.

The force schematic diagram of the riser–subsea wellhead–conductor system is shown in Fig. 1.

According to Ref. [16], the governing equations of the subsea wellhead system are as follows:

$$\begin{cases} E_{\mathrm{r}} I_{\mathrm{r}} \dfrac{\mathrm{d}^4 y}{\mathrm{d}x^4} - T(x) \dfrac{\mathrm{d}^2 y}{\mathrm{d}x^2} - w_{\mathrm{r}} \dfrac{\mathrm{d}y}{\mathrm{d}x} = F_{\mathrm{c}}(x) 0 \le x \le L_{\mathrm{r}} \\ \dfrac{\mathrm{d}^2}{\mathrm{d}x^2} \left(K(x) \dfrac{\mathrm{d}^2 y}{\mathrm{d}x^2} \right) + \dfrac{\mathrm{d}}{\mathrm{d}x} \left(N(x) \dfrac{\mathrm{d}y}{\mathrm{d}x} \right) \\ \quad + D_{\mathrm{s}}(x) p(x, y) = 0 - L_{\mathrm{bop}} \ge x \ge -\left(L_{\mathrm{bop}} + L_{\mathrm{sc}} \right) \end{cases} \tag{1}$$

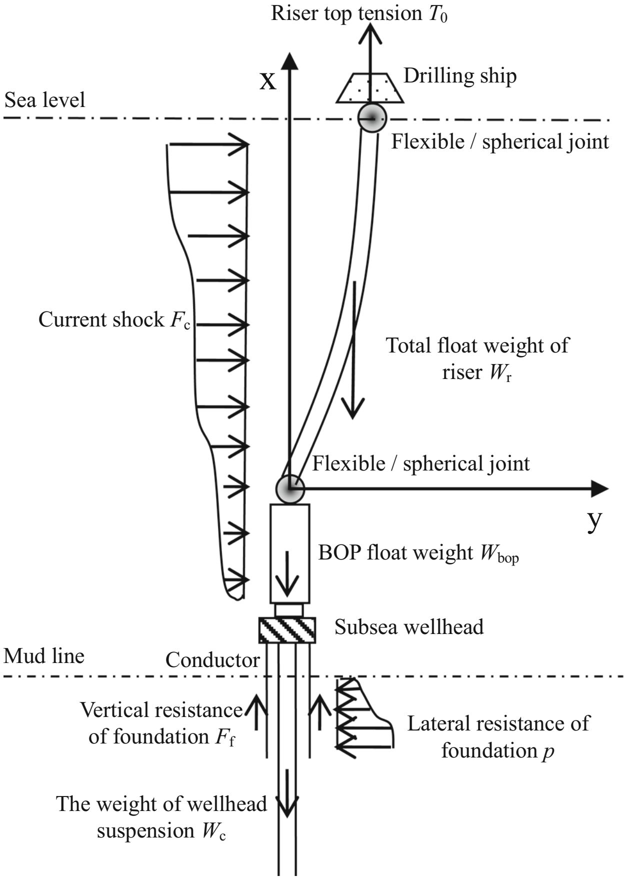

Fig. 1 Force schematic diagram of the riser–subsea wellhead–conductor system

where $E_{\mathrm{r}} I_{\mathrm{r}}$ is the bending stiffness of riser, kN m^2. $T(x)$ is the effective tension of riser, kN. w_{r} is the weight per unit length of riser, kN. $F_{\mathrm{c}}(x)$ is the transverse current impact force in unit length of riser, kN. $K(x)$ is the equivalent bending stiffness of combined pipe (conductor, surface casing, and cement sheath), kN m^2. $N(x)$ is the axial force of combined pipe (conductor, surface casing, and cement sheath), KN. $D_{\mathrm{s}}(x)$ is the diameters of conductor and surface casing, m. $p(x, y)$ is the ground reaction force in unit area of conductor, kPa. L_{bop} is the height of BOP, m. L_{sc} is the length of combined pipe (conductor and surface casing), m.

The calculation equations of the parameters in Eq. (1) are as follows [16,19] (see Eqs. 2–6):

① Weight per unit length of riser, W_{r}:

$$W_{\mathrm{r}} = \frac{\pi}{4}(D_{\mathrm{r}}^2 - d_{\mathrm{r}}^2)\rho_{\mathrm{s}} g + \frac{\pi}{4} d_{\mathrm{r}}^2 \rho_{\mathrm{m}} g - \frac{\pi}{4} D_{\mathrm{r}}^2 \rho_{\mathrm{l}} g - B \tag{2}$$

where D_{r} is the outer diameter of riser, m. d_{r} is the inner diameter of riser, m. ρ_{s} is the density of riser, kg m^{-3}. ρ_{m} is the density of drilling fluid, kg m^{-3}. ρ_{l} is the density of sea water, kg m^{-3}. B is the buoyancy force generated by per unit length of buoyancy section, kN.

② Riser effective tension, $T(x)$:

$$T(x) = T_0 - \int_x^{L_r} W_r \mathrm{d}x \tag{3}$$

where T_0 is the top tension of riser, kN.

③ Transverse current shock force on unit length of riser, $F_c(x)$ [20]:

$$F_c(x) = \frac{1}{2} C_D \rho_l D_r \left(u_t \left(\frac{x}{L_r} \right)^{1/7} + u_w \frac{x}{L_r} \right)^2 \tag{4}$$

where C_D is the resistance coefficient. u_t is the surface tide velocity, $\mathrm{m\,s^{-1}}$. u_w is the surface current velocity, $\mathrm{m\,s^{-1}}$.

④ Equivalent bending stiffness of the combined pipe (conductor, surface casing, and cement sheath) [20–22], K:

$$K = \begin{cases} E_{stl}(I_{so} + I_{si}) \\ E_{stl} I_{si} + 0.8 E_c I_c \\ E_{stl}(I_{so} + I_{si}) + 0.6 E_c I_c \end{cases} \tag{5}$$

where E_{stl} is the elastic modulus of steel of conductor and surface casing, kPa. E_c is the elastic modulus of cement sheath, kPa. I_{so}, I_{si}, I_c are the cross-sectional moment of inertia of conductor, surface casing, and cement sheath, m^4.

⑤ Axial force of the combined pipe composed of conductor, surface casing, and cement sheath, $N(x)$:

$$N(x) = \begin{cases} N_t - W_c(x) \cdot x, & x \geq -x_{ml} \\ N_t - W_c(x) \cdot x + F_f(x) \cdot (x_{ml} - x), & x < -x_{ml} \end{cases} \tag{6}$$

where N_t is the vertical force of subsea wellhead, kN. W_c is the weight of combined pipe per length, kN. $F_f(x)$ is the friction of soil on the unit length of conductor wall, kN. x_{ml} is the height of combined pipe above the mudline, m.

Thus, according to the continuity conditions (see Eq. 7) and the boundary conditions (see Eq. 8), the stress state of subsea wellhead system could be solved by difference method.

$$\begin{cases} y_r = y_c + L_{bop} \cdot \sin(\theta_c) \\ y_{re}\big|_{x=0} = y_r, \qquad y_{cs}\big|_{x=-L_{bop}} = y_c \end{cases} \tag{7}$$

$$\begin{cases} M\big|_{x=L_r} = K_{ru}\theta_{ru}, & y_{re}\big|_{x=L_r} = S_0 \\ M\big|_{x=0} = K_{rd}\theta_{rd}, & y_{re}\big|_{x=0} = y_r \\ M\big|_{x=-L_{bop}} = -M_0, & Q\big|_{x=-L_{bop}} = -H_0 \\ M\big|_{x=-(L_{bop}+L_{sc})} = 0, & Q\big|_{x=-(L_{bop}+L_{sc})} = 0 \end{cases} \tag{8}$$

where θ_c is the rotation angle of subsea wellhead, rad. y_{re} and y_{cs} are the laterally offset of the riser and combined column, m. K_{ru} and K_{rd} are the rotational stiffness of top and bottom of the flexible/spherical joint of riser, $(\mathrm{kN\,m})\,\mathrm{rad}^{-1}$. θ_{ru} and θ_{ru} are the rotation angle of top and bottom of the flexible/spherical joint of riser, rad. y_c and y_r are the lateral deflection of the subsea wellhead and the flexible/spherical joint at the bottom of the riser, m. S_0 is the lateral displacement of the drilling platform, m. M_0 is the bending moment at the bottom of the submarine, kN m. H_0 is the lateral force at the bottom of the subsea wellhead, kN. Q is the shear force at the cross section of the composite pipe column, kN.

3 Analysis of Characteristic Parameters and Its Influencing Factors of Subsea Wellhead Mechanical Stability

3.1 Mechanical Stability Characteristic Parameters of Subsea Wellhead

According to the force analysis of the subsea wellhead system in Fig. 1, it could be known that the riser was deformed by drilling ship drift and current shock, and then, the combined pipe string composed of subsea wellhead and conductor was also deformed. If the deformation was large enough, it would increase the instability risk of subsea wellhead, and it was not conducive to the shape control of drill pipe, which could aggravate the eccentric wear degree of the drill pipe within the annulus of wellhead. Therefore, the characteristic parameters that can quantitatively describe the deformation of the combined pipe string should be found out, so as to analyze the mechanical stability of the subsea wellhead system.

As shown in Fig. 2, after the deformation of the combined pipe string composed of subsea wellhead and conductor, it not only caused the lateral displacement of wellhead (S_w), but also resulted in the deflection angle of combined pipe central axis (θ_w). Thus, S_w and θ_w could be used as characteristic parameters to quantitatively describe the migration degree (mechanical stability) of subsea wellhead.

3.2 The Influence of Different Factors on the Characteristic Parameters of Mechanical Stability of Subsea Wellhead

In deepwater drilling, there are many factors (environmental loads and construction parameters) affecting S_w and θ_w which mainly include: water depth, surface current velocity, surface tide velocity, resistance coefficient, inertia force coefficient, average platform drift, riser tension ratio, height of subsea wellhead above mudline, setting depth of conductor, diameter and thickness of conductor, and setting depth of surface casing.

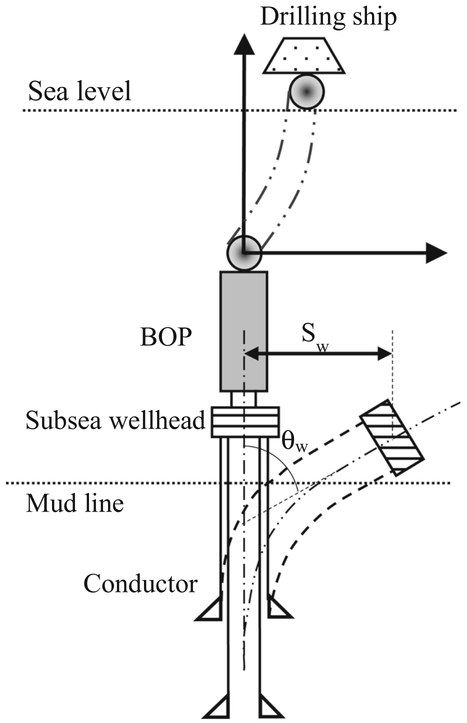

Fig. 2 Schematic diagram of the deformation of combined pipe string (subsea wellhead and conductor)

Through analysis, it could be seen that there were some correlations between some of these factors listed above, which meant they were not independent variables. In the past experiences of data processing, these data need to be processed by orthogonal transform. However, they were all typical environmental loads and construction parameters, which should be considered in the drilling design and construction. And what the drillers would pay more attention to were the sensitivity of a certain parameter to the stability of subsea wellhead when other factors were unchanged in the drilling design. So a set of methods to analyze the sensitivity of each factor were established in this paper.

Firstly, in order to make the calculation results better reflect the influence of factors (x_i) on the characteristic parameters, the value of x_i was specified as follows:

(1) Determine the value range of x_i according to the engineering practice and needs.

(2) Determine the number of values of x_i according to the requirement of calculation accuracy.
Then

$$x_{ij} = x_{i,\min} + \frac{x_{i,\max} - x_{i,\min}}{n} (j - 1) \tag{9}$$

where x_{ij} is the *j*th value of x_i, $j = 1, 2, 3, \ldots, n$.

(3) When the x_i has m ($m > 1$) fixed sizes or values, if $m = 2$, order x_1 and x_2 for the boundary of value range of x_i, and determine other values of x_i using Eq. (9). Otherwise, if $m > 2$, order x_1 and x_{m} for the boundary of value range of x_i, and determine other values of x_i using Eq. (9).

Then, a deepwater well in the South China Sea was taken as the research object. Order $n = 5$, and the characteristic parameters and their influence factors of mechanical stability of subsea wellhead are studied by using the model established in Sect. 2. The basic parameters of the deepwater well are listed in Table 1, and the calculation results are listed in Table 2.

As listed in Table 2, the setting depth of conductor, the increment of non-drainage shear strength per 10 m, and the increment of submerged unit weight per 10 m had little or no influence on the characteristic parameters in their selected value range. So in order to explore the influence law, the three parameters need to be recalculated with more refined values.

3.3 Sensitivity Analysis of Various Factors on the Mechanical Stability of Subsea Wellhead

Secondly, in order to study the sensitivity of different factors to the characteristic parameters of subsea wellhead stability, the x_{ij} need to be dimensionless. According to the principle of Sect. 3.2, the values of x_i belong to the uniform, so the data in Table 2 could be processed to dimensionless by using dimensionless method of "center" [23] (calculation equation see Eq. 10). The results are listed in Table 3.

$$x'_{ij} = \frac{x_{ij} - \bar{x}_j}{S_j} \tag{10}$$

where $\bar{x}_j$ is the average value of x_j, and S_j is the mean square deviation of x_j.

In order to make the influence law of dimensionless factors on the mechanical stability of subsea wellhead more intuitive, the data in Table 3 are plotted. The dimensionless factor was taken as the horizontal coordinate, and the wellhead displacement or deflection angle was taken as the vertical coordinate, which are shown in Figs. 3 and 4.

With reference to data in Figs. 3 and 4, it could be seen that there was a big difference between the influence of different dimensionless factors on subsea wellhead displacement and deviation angle. However, for the dimensionless factors separately, its influence on subsea wellhead displacement and deviation angle are basically the same. Most of the factors are linear correlation, only the effects of very few factors are nonlinear and the nonlinear degree is small, which could be approximated as a linear correlation. According to their characteristics, it could be regressed using the least square method [24].

Table 1 Basic parameters of the deepwater well

Environmental loads	Value	Engineering parameters	Value	Material properties	Value
Platform mean drift/(% water depth)	3	Water depth (m)	1525	Elastic modulus of steel (GPa)	210
Surface current speed ($\mathrm{m\,s^{-1}}$)	1.2	Mud density ($\mathrm{kg\,m^{-3}}$)	1180	Steel density ($\mathrm{kg\,m^{-3}}$)	7850
Surface tide speed ($\mathrm{m\,s^{-1}}$)	0.6	Riser length (m)	1525	Riser diameter (mm)	533.4
Resistance coefficient	0.8	Riser tension ratio	1.5	Riser wall thickness (mm)	25.4
Seawater density ($\mathrm{kg\,m^{-3}}$)	1030	Setting depth of conductor (m)	80	Unit weight of jet drilling tool (kN m)	3.6
Buoyancy coefficient in seawater	0.85	Height of wellhead above mudline (m)	3.2	Conductor diameter (mm)	914.4
Number of subsea soil layers	10	Wellhead suspension weight (kN)	3000	Conductor wall thickness (mm)	25.4
Initial non-drainage shear strength (Kpa)	20	Setting depth of surface casing (m)	685	Surface casing diameter (mm)	508
Increment of non-drainage shear strength per 10 m (Kpa)	15	Height of BOP (m)	18	Surface casing wall thickness (mm)	12.7
Initial soil submerged unit weight ($\mathrm{kN\,m^{-3}}$)	7.0	Weight of BOP (kN)	2000	Unit weight of surface casing (kN m)	2.1
Increment of submerged unit weight per 10 m (kN m)	0.5	Equivalent diameter of BOP (m)	1	Elastic modulus of cement sheath (GPa)	18

Table 2 Influence of various factors on the characteristic parameters of mechanical stability of subsea wellhead

Water depth (m)	S_w (m)	θ_w (°)	Surface current speed ($\mathrm{m\,s^{-1}}$)	S_w (m)	θ_w (°)	Surface tide speed ($\mathrm{m\,s^{-1}}$)	S_w (m)	θ_w (°)
1325	0.276	2.461	0.8	0.189	1.744	0.4	0.303	2.684
1425	0.309	2.727	1.0	0.257	2.322	0.5	0.321	2.828
1525	0.342	2.983	1.2	0.342	2.983	0.6	0.342	2.983
1625	0.375	3.244	1.4	0.447	3.773	0.7	0.363	3.144
1725	0.409	3.501	1.6	0.571	4.683	0.8	0.385	3.311
Drag coefficient	S_w (m)	θ_w (°)	Lift force of buoyancy block (kN)	S_w (m)	θ_w (°)	Platform mean drift/(% water depth)	S_w (m)	θ_w (°)
0.6	0.259	2.336	1750	0.360	3.129	1	0.271	2.432
0.7	0.299	2.653	2000	0.351	3.057	2	0.306	2.707
0.8	0.342	2.983	2250	0.342	2.983	3	0.342	2.983
0.9	0.386	3.319	2500	0.332	2.906	4	0.379	3.268
1.0	0.431	3.656	2750	0.324	2.834	5	0.418	3.554
Riser tension ratio	S_w (m)	θ_w (°)	Setting depth of conductor (m)	S_w (m)	θ_w (°)	Height of wellhead above mudline (m)	S_w (m)	θ_w (°)
1.1	0.130	1.270	70	0.342	2.983	2.6	0.324	2.898
1.3	0.244	2.204	75	0.342	2.983	2.8	0.329	2.923
1.5	0.342	2.983	80	0.342	2.983	3.0	0.337	2.962
1.7	0.434	3.708	85	0.342	2.983	3.2	0.342	2.983
1.9	0.516	4.374	90	0.342	2.983	3.4	0.347	3.010

Table 2 continued

Conductor diameter (mm)	S_w (m)	θ_w (°)	Conductor wall thickness (mm)	S_w (m)	θ_w (°)	Mud density (kg m^{-3})	S_w (m)	θ_w (°)
762.0	0.637	5.661	25.400	0.342	2.983	1080	0.331	2.899
800.1	0.533	4.731	28.575	0.315	2.735	1180	0.342	2.983
838.2	0.455	4.019	31.750	0.294	2.535	1280	0.352	3.064
876.3	0.393	3.451	34.925	0.276	2.369	1380	0.361	3.141
914.4	0.342	2.983	38.100	0.261	2.225	1480	0.370	3.217
Riser diameter (mm)	S_w (m)	θ_w (°)	Elastic modulus of cement sheath (GPa)	S_w (m)	θ_w (°)	Initial soil submerged unit weight (kN m^{-3})	S_w (m)	θ_w (°)
406.4	0.217	1.982	8	0.370	3.252	4	0.354	3.037
457.2	0.274	2.374	13	0.356	3.112	5.5	0.348	3.010
508	0.324	2.770	18	0.342	2.983	7	0.342	2.984
558.8	0.375	3.167	23	0.330	2.870	8.5	0.336	2.957
609.6	0.417	3.571	28	0.318	2.761	10	0.330	2.930
Initial non-drainage shear strength (Kpa)	S_w (m)	θ_w (°)	Increment of submerged unit weight per 10 m (kN m^{-3})	S_w (m)	θ_w (°)	Increment of non-drainage shear strength per 10 m (Kpa)	S_w (m)	θ_w (°)
10	0.441	3.415	0.1	0.342	2.983	5	0.345	3.005
15	0.385	3.175	0.3	0.342	2.983	10	0.342	2.991
20	0.342	2.983	0.5	0.342	2.983	15	0.342	2.983
25	0.311	2.841	0.7	0.342	2.983	20	0.341	2.977
30	0.287	2.728	0.9	0.342	2.983	25	0.339	2.966

Take the regression analysis of the effects of water depth H_i on subsea wellhead displacement S_{wi} as an example. Assume the best linear fitting equation was $S'_{wi} = aH_i + b$, then the regression equation of water depth H_i and wellhead displacement S_{wi} could be obtained:

$$S'_{wi} = \frac{\sum H_i \sum S_{wi} - n \sum H_i S_{wi}}{\left(\sum H_i\right)^2 - n \sum H_i^2} H_i + \frac{\sum H_i S_{wi} \sum H_i - \sum S_{wi} \sum H_i^2}{\left(\sum H_i\right)^2 - n \sum H_i^2} \tag{11}$$

In order to characterize the fit degree between the regression equation and the original data, the correlation coefficient R was introduced, and its value range was $[-1, 1]$.

$$R = \frac{\sum \left(H_i - \bar{H}_i\right) \sum \left(S_{wi} - \bar{S}_{wi}\right)}{\sqrt{\sum \left(H_i - \bar{H}_i\right)^2} \sqrt{\sum \left(S_{wi} - \bar{S}_{wi}\right)^2}} \tag{12}$$

R^2 was the coefficient of determination, and its value range was [0, 1]. It indicated the correlation degree between S'_{wi} and S_{wi}. The closer R^2 was to 1, the more they were related.

According to Eqs. (11) and (12), the regression equations of non-dimensional factors could be obtained as follows:

$$S_w = \begin{cases} 0.0525x_1 + 0.3422\,(R^2 = 1) \\ 0.1508x_2 + 0.3612\,(R^2 = 0.986) \\ 0.0326x_3 + 0.3428\,(R^2 = 0.999) \\ 0.0681x_4 + 0.3434\,(R^2 = 1) \\ -0.0144x_7 + 0.3418\,(R^2 = 0.999) \\ 0.058x_6 + 0.3432\,(R^2 = 0.99) \\ 0.1521x_7 + 0.3332\,(R^2 = 0.996) \\ 0.0093x_8 + 0.3358\,(R^2 = 0.992) \\ -0.1154x_9 + 0.472\,(R^2 = 0.980) \\ -0.0318x_{10} + 0.2976\,(R^2 = 0.987) \\ 0.0153x_{11} + 0.3512\,(R^2 = 0.998) \\ 0.0829x_{12} + 0.3237\,(R^2 = 1) \\ -0.0206x_{13} + 0.3432\,(R^2 = 0.998) \\ -0.0095x_{14} + 0.342\,(R^2 = 1) \\ -0.0604x_{15} + 0.3532\,(R^2 = 0.972) \\ 10^{-7}x_{16} + 0.342(R^2 = 0.999) \\ -0.0022x_{17} + 0.342\,(R^2 = 0.980) \end{cases}$$

Table 3 Influence of various factors on the characteristic parameters of mechanical stability of subsea wellhead after the dimensionless processing

Water depth (m)	S_w (m)	θ_w (°)	Surface current speed ($m\,s^{-1}$)	S_w (m)	θ_w (°)	Surface tide speed ($m\,s^{-1}$)	S_w (m)	θ_w (°)
− 1.265	0.276	2.461	−1.265	0.189	1.744	− 1.265	0.303	2.684
− 0.632	0.309	2.727	−0.632	0.257	2.322	− 0.632	0.321	2.828
0.000	0.342	2.983	0.000	0.342	2.983	0.000	0.342	2.983
0.632	0.375	3.244	0.632	0.447	3.773	0.632	0.363	3.144
1.265	0.409	3.501	1.265	0.571	4.683	1.265	0.385	3.311

Drag coefficient	S_w/m	θ_w/°	Lift force of buoyancy block/kN	S_w/m	θ_w/°	Platform mean drift/(% water depth)	S_w/m	θ_w/°
− 1.265	0.259	2.336	− 1.265	0.36	3.129	− 1.265	0.271	2.432
− 0.632	0.299	2.653	− 0.632	0.351	3.057	− 0.632	0.306	2.707
0.000	0.342	2.983	0.000	0.342	2.983	0.000	0.342	2.983
0.632	0.386	3.319	0.632	0.332	2.906	0.632	0.379	3.268
1.265	0.431	3.656	1.265	0.324	2.834	1.265	0.418	3.554

Riser tension ratio	S_w (m)	θ_w	Height of wellhead above mudline (m)	S_w (m)	θ_w	Conductor diameter (mm)	S_w (m)	θ_w
−1.265	0.13	1.27	−1.265	0.324	2.898	−1.265	0.637	5.661
−0.632	0.244	2.204	−0.632	0.329	2.923	−0.632	0.533	4.731
0.000	0.342	2.983	0.000	0.337	2.962	0.000	0.455	4.019
0.632	0.434	3.708	0.632	0.342	2.983	0.632	0.393	3.451
1.265	0.516	4.374	1.265	0.347	3.01	1.265	0.342	2.983

Conductor wall thickness (mm)	S_w (m)	θ_w (°)	Mud density ($kg\,m^{-3}$)	S_w (m)	θ_w (°)	Riser diameter (mm)	S_w (m)	θ_w (°)
−1.265	0.342	2.983	−1.265	0.331	2.899	−1.265	0.217	1.982
−0.632	0.315	2.735	−0.632	0.342	2.983	−0.632	0.274	2.374
0.000	0.294	2.535	0.000	0.352	3.064	0.000	0.324	2.770
0.632	0.276	2.369	0.632	0.361	3.141	0.632	0.375	3.167
1.265	0.261	2.225	1.265	0.37	3.217	1.265	0.417	3.571

Elastic modulus of cement sheath (GPa)	S_w (m)	θ_w (°)	Initial soil submerged unit weight ($kN\,m^{-3}$)	S_w (m)	θ_w (°)	Initial non-drainage shear strength (Kpa)	S_w (m)	θ_w (°)
−1.265	0.37	3.252	−1.265	0.354	3.037	−1.265	0.441	3.415
−0.632	0.356	3.112	−0.632	0.348	3.010	−0.632	0.385	3.175
0.000	0.342	2.983	0.000	0.342	2.984	0.000	0.342	2.983
0.632	0.33	2.87	0.632	0.336	2.957	0.632	0.311	2.841
1.265	0.318	2.761	1.265	0.330	2.930	1.265	0.287	2.728

Increment of submerged unit weight per 1 m ($kN\,m^{-3}$)	S_w (m)	θ_w (°)	Increment of non-drainage shear strength per 1 m (Kpa)	S_w (m)	θ_w (°)
−1.265	0.342	2.983	−1.265	0.345	3.005
−0.632	0.342	2.983	−0.632	0.342	2.991
0.000	0.342	2.983	0.000	0.342	2.983
0.632	0.342	2.983	0.632	0.341	2.977
1.265	0.342	2.983	1.265	0.339	2.966

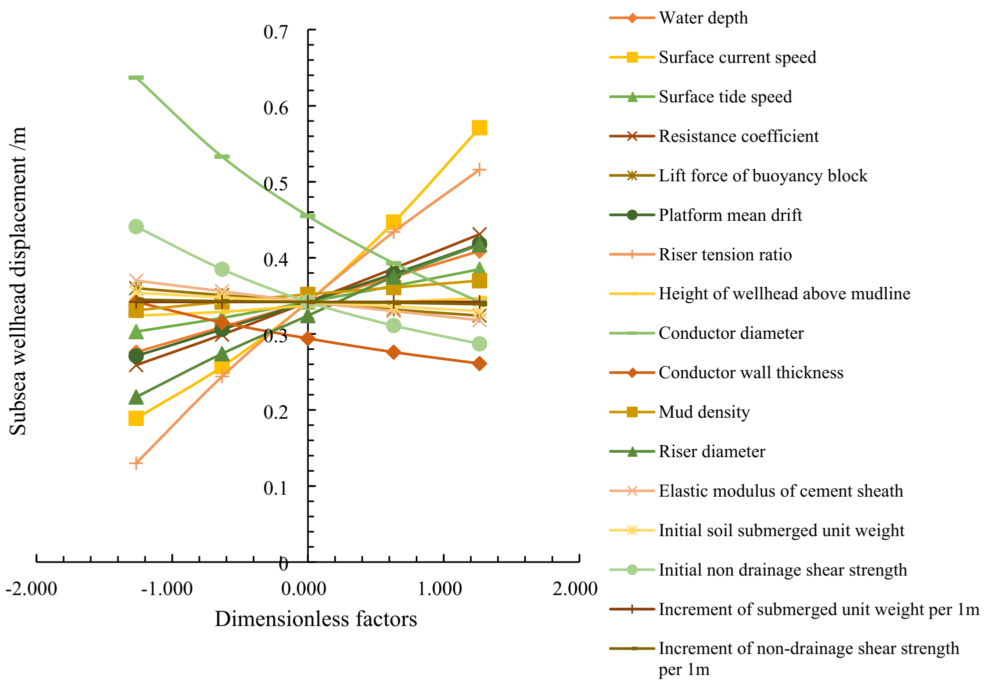

Fig. 3 Influence of dimensionless factors on the subsea wellhead displacement

$$\theta_w = \begin{cases} 0.4106x_1 + 2.9832\,(R^2 = 1) \\ 1.1588x_2 + 3.101\,(R^2 = 0.992) \\ 0.2482x_3 + 2.99\,(R^2 = 0.999) \\ 0.5227x_4 + 2.9894\,(R^2 = 1) \\ -0.1172x_5 + 2.9818\,(R^2 = 1) \\ 0.4435x_6 + 2.9888\,(R^2 = 1) \\ 1.2194x_7 + 2.9078\,(R^2 = 0.996) \\ 0.0449x_8 + 2.9552\,(R^2 = 0.992) \\ -1.0492x_9 + 4.169\,(R^2 = 0.982) \\ -0.2976x_{10} + 2.5694\,(R^2 = 0.988) \\ 0.1255x_{11} + 3.0608\,(R^2 = 1) \\ 0.6249x_{12} + 2.7709\,(R^2 = 1) \\ -0.1935x_{13} + 2.9956\,(R^2 = 0.997) \\ -0.0422x_{14} + 2.9836\,(R^2 = 1) \\ -0.2701x_{15} + 3.0284\,(R^2 = 0.978) \\ -10^{-16}x_{16} + 2.983(R^2 = 0.999) \\ -0.0145x_{17} + 2.9844\,(R^2 = 0.981) \end{cases} \tag{13}$$

where S_w is the subsea wellhead displacement, m; θ_w is the deflection angle of subsea wellhead, degree; x_i $(i = 1, 2, 3, \ldots, 15, 16, 17)$ is, respectively, the dimensionless value of water depth, surface current velocity, surface tied velocity, resistance coefficient, lift force of buoyancy block, platform mean drift, riser tension ratio, height of subsea wellhead above mud line, conductor diameter, conductor wall thickness, drilling fluid density, riser diameter, elastic modulus of cement sheath, initial soil submerged unit weight, initial non-drainage shear strength, increment of submerged unit weight per 1 m, and increment of non-drainage shear strength per 1 m. The value range of x_i is [− 1.265, 1.265].

For the regression equations $y_i = a_i x_i + b_i$, $|a_i|$ directly reflected the sensitivity of x_i to y_i in the interval [− 1.265, 1.265]. That was, the bigger $|a_i|$, the greater the change of y_i caused by the same change of dimensionless factors. So $|a_i|$ could be used as an index to evaluate the sensitivity of x_i to y_i, which was defined as the sensitive factor of x_i to y_i.

Meanwhile, the integral Y_i (see Eq. 14) of each line in the interval $[x_{i\,\min}, x_{i\,\max}]$ reflected the overall influent level of x_i on y_i. And the greater the Y_i, the x_i was more likely to cause the displacement and angle deviation of subsea wellhead in its value range. Therefore, Y_i could be used as an index to evaluate the relative effect of x_i on y_i.

$$Y_i = \int_{x_{i\,\min}}^{x_{i\,\max}} (ax_i + b)\mathrm{d}x_i \tag{14}$$

For the value range of x_i was all [− 1.265, 1.265], and it was symmetric with the Y axis, Y_i could be replaced by the intercept b_i when the comparison was made between x_i and y_i. Define b_i was the baseline for the impact of x_i on y_i.

The sensitive factor $|a_i|$ and impact baseline b_i of Eq. (13) had been calculated and sorted, as listed in Table 4.

Based on the results in Table 4, and according to the relative order of magnitude and size of $|a_i|$ and b_i, factors affected wellhead displacement and deflection angle greater and more sensitively for the sample deepwater well could be screened.

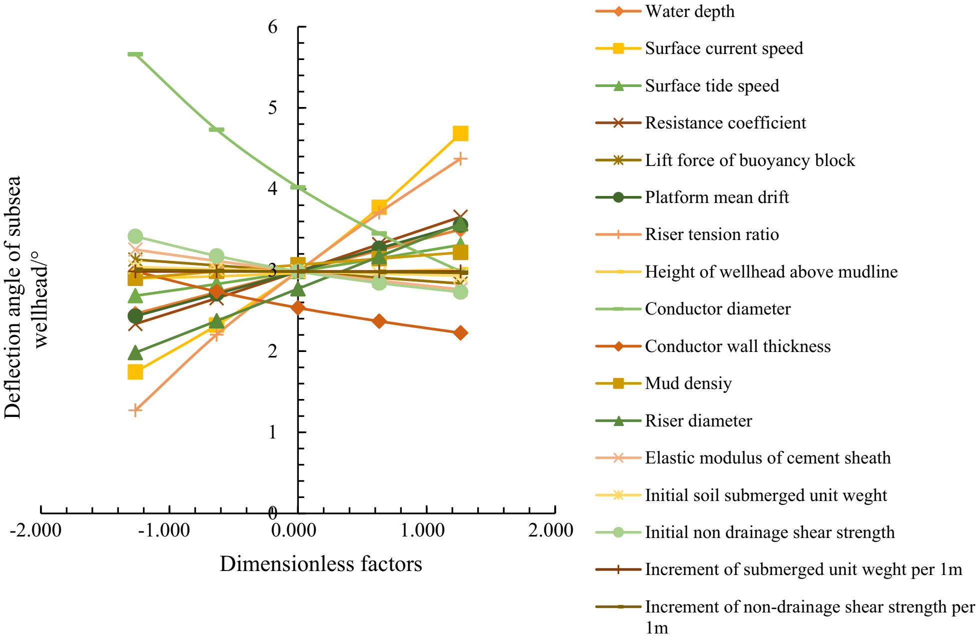

Fig. 4 Influence of dimensionless factors on the subsea wellhead deflection angle

Table 4 Sensitive factor and impact baseline of x_i to y_i and its sequencing

Dimensionless factors	Displacement of subsea wellhead S_w				Deflection angle of subsea wellhead θ_w			
	$\lvert a_i \rvert$	Sorting	b_i	Sorting	$\lvert a_i \rvert$	Sorting	b_i	Sorting
x_1	0.0525	8	0.3422	9	0.4106	7	2.9832	11
x_2	0.1508	2	0.3612	2	1.1588	2	3.101	2
x_3	0.0326	9	0.3428	8	0.2482	10	2.99	6
x_4	0.0681	5	0.3434	5	0.5227	5	2.9894	7
x_5	0.0144	13	0.3418	13	0.1172	13	2.9818	13
x_6	0.058	7	0.3432	6	0.4435	6	2.9888	8
x_7	0.1521	1	0.3332	15	1.2194	1	2.9078	15
x_8	0.0093	15	0.3358	14	0.0449	14	2.9552	14
x_9	0.1154	3	0.472	1	1.0492	3	4.169	1
x_{10}	0.0318	10	0.2976	17	0.2976	8	2.5694	17
x_{11}	0.0153	12	0.3512	4	0.1255	12	3.0608	3
x_{12}	0.0829	4	0.3237	16	0.6249	4	2.7709	16
x_{13}	0.0206	11	0.3432	7	0.1935	11	2.9956	5
x_{14}	0.0095	14	0.342	10	0.0422	15	2.9836	10
x_{15}	0.0604	6	0.3532	3	0.2701	9	3.0284	4
x_{16}	1×10^{-7}	17	0.342	11	10^{-16}	17	2.983	12
x_{17}	0.0022	16	0.342	12	0.0145	16	2.9844	9

(1) Six factors that were the most sensitive to the displacement of subsea wellhead (sort from the strongest to the weakest one): ① riser tension ratio, ② surface current velocity, ③ conductor diameter, ④ riser diameter, ⑤ resistance coefficient, ⑥ initial soil submerged unit weight

(2) Six factors that had the most impact on the displacement of subsea wellhead (sort from the strongest to the weakest one): ① riser diameter, ② surface current velocity, ③ initial soil submerged unit weight, ④ mud density, ⑤ resistance coefficient, ⑥ platform mean drift

(3) Six factors that were the most sensitive to the deflection angle of subsea wellhead (sort from the strongest to

the weakest one): ① riser tension ratio, ② surface current velocity, ③ conductor diameter, ④ riser diameter> resistance coefficient, ⑥ platform mean drift

(4) Six factors that had the most impact on the deflection angle of subsea wellhead (sort from the strongest to the weakest one): ① conductor diameter, ② surface current velocity, ③ mud density, ④ initial soil submerged unit weight, ⑤ elastic modulus of cement sheath, ⑥ surface tide velocity

The bigger the impact baseline b_i was, which meant the average impact level of x_i on y_i was greater, the worse the mechanical stability of subsea wellhead was. The greater the sensitivity factor $|a_i|$ was, the more favorable the y_i could be reduced by adjusting x_i, and it was the primary factor should be considered to improve the mechanical stability of subsea wellhead.

4 Risk Assessment Method for Subsea Wellhead Instability

4.1 Uncertainty Analysis of Sensitivity Parameters

Factors that were the most sensitive to the wellhead mechanical stability of instance well are filtered in Sect. 3.3. Among these sensitive factors, initial soil submerged unit weight is environmental load, which could be obtained more accurately through experiments and measurements. Conductor diameter, riser diameter, and riser tension ratio are construction parameters, which are also possible to control and determine accurately. Surface current velocity and platform mean drift are time-varying parameters, and the maximum allowable value of them should be calculated by regression equation, so that other construction parameters could be controlled reasonably. However, the resistance coefficient is empirical coefficient in the calculation model of the mechanical stability of subsea wellhead. According to ⟨Rules for Construction and Classification of Mobile Offshore Drilling Units⟩ [25], the range of resistance coefficient is 0.6–1.2. Meanwhile, for the calculation of instance well, the variation range of wellhead displacement was [0.259, 0.5158] m and the variation range of deflection angle was [2.336, 4.3118]° when the resistance coefficient was changed in the interval [0.6, 1.2]. Obviously, the difference of calculation results of wellhead displacement and deflection angle was nearly 0.3 m and 2° when the value of resistance coefficient was selected as 0.6 and 1.2 in the calculation process. This shows that the value of resistance coefficient has great influence on the mechanical stability of subsea wellhead, and it is necessary to integrate the uncertainty of the coefficient into the risk identification of the wellhead instability.

The determination of resistance coefficient C_D is affected by many factors, such as the current Reynolds number, the riser wall roughness, the structure of riser system and its biological attachment and so on. It is an empirical coefficient related to the marine environment and engineering structure, and it is difficult to measure or obtain its accurate value because that the resistance coefficient is always changed with marine environment and engineering conditions. Therefore, it can be defined as parameter obey a certain distribution form with probability information. Then, the characteristic parameters of wellhead corresponding to different probability in the distribution form of C_D can be calculated. It is convenient to integrate the risk probability information caused by C_D into the identification of instability risk of subsea wellhead, which could avoid the instability risk caused by inaccurate value of C_D to the maximum extent.

Forms of numerical distribution mainly include: average distribution, triangular distribution, and normal distribution. According to the characteristics of resistance coefficient, the normal distribution was chosen as the distribution form, and there were two main reasons:

(1) Under the particular condition of marine environment and engineering structure, true value of resistance coefficient should tend to a certain value.

(2) The marine environment is constantly changing, and the condition of the riser wall roughness and its biological attachment also change over time. The value of C_D will fluctuate in a certain range in the whole process of deepwater drilling.

Thus, the probability density and cumulative probability distribution function of the normal distribution of C_D are, respectively, as follows:

$$p(C_\text{D}) = \frac{1}{\sqrt{2\pi}\sigma} \mathrm{e}^{-\frac{(C_\text{D}-\mu)^2}{2\sigma^2}} \tag{15}$$

$$F(C_\text{D}) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{C_\text{D}} \mathrm{e}^{-\frac{(t-\mu)^2}{2\sigma^2}} \mathrm{d}t \tag{16}$$

where μ is the expectation; it represents the average value of C_D; σ is the standard deviation; it represents the discrete degree of distribution of C_D; the smaller the σ is, the more concentrated the C_D distributes on both sides of μ.

According to the meaning of C_D, μ could be defined as the center value of C_D, and its value should be determined according to the marine environment and the engineering structure. The σ could be defined as the fluctuation coefficient of C_D, and its value should be determined according to the degree of change in the marine environment and the requirements of risk management and control.

4.2 Risk Identification Method for Wellhead Instability

Based on the uncertainty analysis of sensitive parameters in Sect. 4.1, the risk identification of subsea wellhead instability could be carried out according to the following steps:

(1) According to the requirements of risk management and control, the safety limit of subsea wellhead displacement and deflection angle—S_{wm} and θ_{wm}—should be determined first. Meanwhile, the center value μ and the fluctuation coefficient σ of $C_{\mathrm{D}}(\mu, \sigma)$ could be determined according to the marine environment, engineering structure and requirements of risk management and control.

(2) Make the resistance coefficient C_{D} take its center value μ. Using the calculation results in Sect. 3, the relationship between surface current velocity u_{w} (or platform mean drift S_0) and subsea wellhead displacement (or deflection angle) could be fitted, respectively. Then, the fitting equation of each variable could be obtained: $S_{\mathrm{w}}(u_{\mathrm{w}})$, $\theta_{\mathrm{w}}(u_{\mathrm{w}})$, $S_{\mathrm{w}}(S_0)$, and $\theta_{\mathrm{w}}(S_0)$.

(3) Let $S_{\mathrm{w}}(u_{\mathrm{w}}) = S_{\mathrm{wm}}, \theta_{\mathrm{w}}(u_{\mathrm{w}}) = \theta_{\mathrm{wm}}, S_{\mathrm{w}}(S_0) = S_{\mathrm{wm}}$, and $\theta_{\mathrm{w}}(S_0) = \theta_{\mathrm{wm}}$, u_{w1}, u_{w2}, S_{01}, and S_{02}, which are satisfied to the equations that could be obtained. Then, the maximum current velocity that could ensure the stability of subsea wellhead is $u_{\mathrm{wm}} = \min\{u_{\mathrm{w1}}, u_{\mathrm{w2}}\}$, and the maximum platform mean drift that could ensure the stability of subsea wellhead is $S_{0\mathrm{m}} = \min\{S_{01}, S_{02}\}$.

(4) According to the distribution form of C_{D}, repeat steps (2) and (3) by changing the value of C_{D}, and the distribution form of u_{wm} and $S_{0\mathrm{m}}$ could be determined. The probability density and cumulative probability distribution are shown in Figs. 5 and 6, respectively. Therefore, when the values of surface current velocity and platform mean drift were u_{w} and S_{w}, respectively, the probability of subsea wellhead instability is:

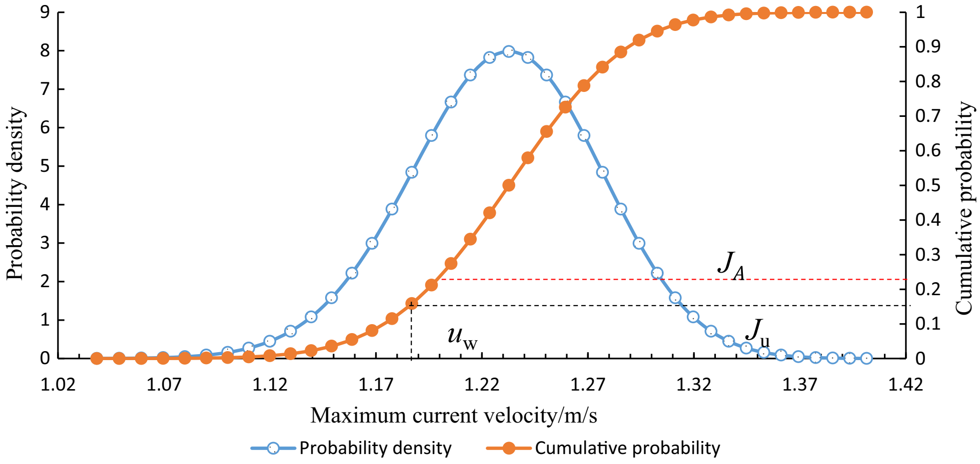

Fig. 5 Probability density and cumulative probability distribution of the maximum current velocity

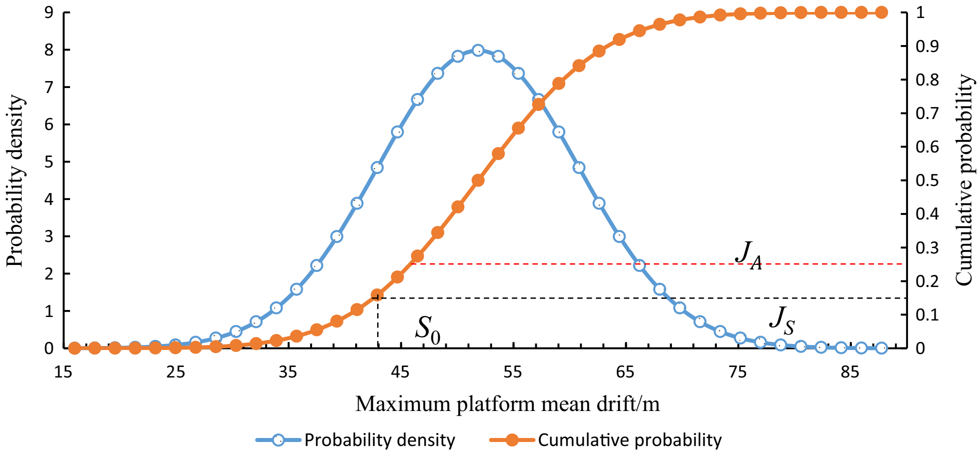

Fig. 6 Probability density and cumulative probability distribution of the maximum platform mean drift

$$P_{\mathrm{h}} = \max\{J_{\mathrm{u}}, J_S\} \quad (17)$$

where J_{u} is the cumulative probability of u_{w}; it represents the probability that the maximum current velocity is less than u_{w}. J_{S} is the cumulative probability of S_{w}; it represents the probability that the maximum platform mean drift is less than S_{w}.

(5) At the same time, in order to facilitate the on-site real-time monitoring, the risk threshold J_{A} (it is the safety limit of the risk of wellhead instability, and the greater the value is, the lower its reliability is) could be determined according to the actual situation. Then, the corresponding surface current velocity u_{wA} and platform mean drift S_{wA} could be calculated. When the monitoring value of $u_{\mathrm{w}} > u_{\mathrm{wA}}$ or $S_{\mathrm{w}} > S_{\mathrm{wA}}$, there are reasons to believe the subsea wellhead has instability risk, and we should immediately take appropriate measures to reduce the risk of instability.

As a note, the safety limit of subsea wellhead displacement and deflection angle—S_{wm} and θ_{wm}—mentioned in step (1) are the maximum allowable value of S_{w} and θ_{w} to ensure the stability of subsea wellhead and the safety of riser, which need to be determined with a comprehensive consideration of various factors, such as whether the subsequent casing could be smoothly down through the wellhead, the eccentric wear degree of drill pipe, the condition of vortex induced vibration of riser, and the height of subsea wellhead above mudline and so on.

5 Case Study

Take the deepwater well in Sect. 3.2 as an example; its mechanical stability of subsea wellhead was analyzed by using the method introduced in Ref. [16] and the method established in this paper.

5.1 The Results Calculated Using the Previous Method

Take the resistance coefficient as the common value -0.8, the displacement and offset angle of the subsea wellhead could be obtained as follows:

$$S_{\mathrm{w}} = 0.342\,\mathrm{m}, \quad \theta_{\mathrm{w}} = 2.983^\circ$$

It could be seen that the result obtained by this method is a single value, and the result can only reflect the deformation characteristics of the subsea wellhead under this condition and cannot indicate whether or not the instability occurs and the probability of its occurrence. Moreover, the resistance coefficient is based on empirical values. According to the analysis of Sect. 4.1, the calculation result has certain uncertainty.

5.2 The Results Calculated Using the Method Established in this Paper

(1) According to risk control requirements, the safety limit of subsea wellhead displacement was determined as $S_{\mathrm{wm}} = 0.37$ m, and the safety limit of subsea wellhead deflection angle was determined as $\theta_{\mathrm{wm}} = 3.1^\circ$. At the same time, according to the marine environment, engineering structure, and risk control requirements, the center value of C_{D} was determined as $\mu = 0.8$, and the fluctuation coefficient of C_{D} was determined as $\sigma = 0.05$, so C_{D} meet the normal distribution of C_{D} (0.8, 0.05).

(2) Using the calculated results of Sect. 3.2, the resistance coefficient C_{D} was given its center value of 0.8. The relationship between surface current velocity u_{w} (or platform mean drift S_0) and subsea wellhead displacement (or deflection angle) was fitted as follows:

$$\begin{aligned} S_{\mathrm{w}}(u_{\mathrm{w}}) &= 0.2357u_{\mathrm{w}}^2 - 0.0887u_{\mathrm{w}} + 0.1094\,(R^2 = 1) \\ S_{\mathrm{w}}(S_0) &= 0.0367S_0 + 0.2331\,(R^2 = 0.9996) \\ \theta_{\mathrm{w}}(u_{\mathrm{w}}) &= 1.4161u_{\mathrm{w}}^2 + 0.2659u_{\mathrm{w}} + 0.6295\,(R^2 = 1) \\ \theta_{\mathrm{w}}(S_0) &= 0.2805S_0 + 2.1473,\ (R^2 = 0.9999) \end{aligned}$$

(3) Let $S_{\mathrm{w}}(u_{\mathrm{w}}) = S_{\mathrm{w}}(S_0) = 0.37\,\mathrm{m}, \theta_{\mathrm{w}}(u_{\mathrm{w}}) = \theta_{\mathrm{w}}(S_0) = 3.1^\circ$, then $u_{\mathrm{w1}} = 1.26\,\mathrm{m\,s^{-1}}, S_{01} = 3.73$ (%water depth) $= 56.88$ m, $u_{\mathrm{w2}} = 1.23\,\mathrm{m\,s^{-1}}, S_{02} = 3.40$ (%water depth) $= 51.85$ m. And then the maximum current velocity that could ensure the stability of subsea wellhead was $u_{\mathrm{wm}} = \min\{1.26, 1.23\} = 1.23\ \mathrm{m\,s^{-1}}$, and the maximum platform mean drift that could ensure the stability of subsea wellhead was $S_{0\mathrm{m}} = \min\{56.88, 51.85\} = 51.85$ m.

(4) According to the distribution form of C_{D}, repeat steps (2) and (3) by changing the value of C_{D}, and the distribution form of u_{wm} and $S_{0\mathrm{m}}$ could be determined. The probability density and cumulative probability distribution are shown in Figs. 7 and 8, respectively. Therefore, when values of surface current velocity and platform mean drift were, respectively, $u_{\mathrm{w}} = 1.2\ \mathrm{m\,s^{-1}}$ and $S_{\mathrm{w}} = 3\% = 45.75\,\mathrm{m}$, the probability of subsea wellhead instability was:

$$P_{\mathrm{h}} = \max\{J_{\mathrm{u}}, J_{\mathrm{S}}\} = \max\{0.22, 0.24\} = 0.24 = 24\%$$

(5) At the same time, in order to facilitate the on-site real-time monitoring, the risk threshold J_{A} was set as 15%, which meant the risk of wellhead instability was controlled within 15%. The corresponding surface current velocity $u_{\mathrm{wA}} = 1.188\ \mathrm{m\,s^{-1}}$ and the platform mean

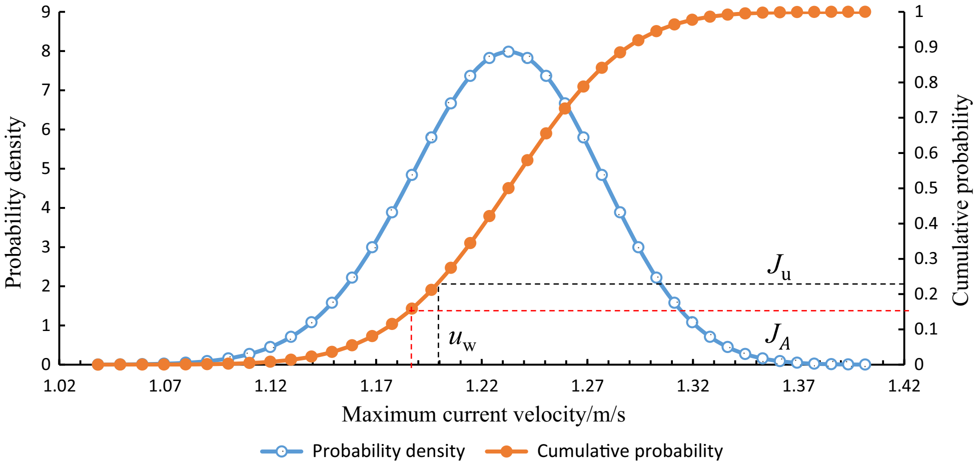

Fig. 7 Probability density and cumulative probability distribution of the maximum current velocity of target well

drift $S_{wA} = 43$ m. When the monitoring value of $u_w > 1.188\ \mathrm{m\,s^{-1}}$ or $S_w > 43$ m, there are reasons to believe the subsea wellhead has instability risk and should immediately take appropriate measures to reduce the risk of instability.

Thus, according to the selected parameters, including $\mu = 0.8$, $\sigma = 0.05$, $S_{wm} = 0.37$ m, and $\theta_{wm} = 3.1°$, it could be determined that the probability of subsea wellhead instability of the target deepwater well was 24%. At the same time, it should be guaranteed that $S_w < 43$ m in the construction process and the monitoring value of $u_w < 1.188\ \mathrm{m\,s^{-1}}$.

In order to improve the mechanical stability of subsea wellhead of the instance well, the following measures could be adopted according to the sensitivity analysis of factors in Sect. 3.3:

(1) Riser tension: it is better to reduce the top tension of riser as much as possible on the basis of ensuring the deformation control and improving the force condition of the riser. At the same time, it is an important parameter to adjust the stability of subsea wellhead, and it needs to be adjusted timely according to the actual needs in the drilling process.
(2) Conductor diameter: it is better to choose big size conductor within the allowable range.
(3) Initial non-drainage shear strength: it is better to select the region with greater initial non-drainage shear strength of subsea shallow soil to carry out the drilling process.
(4) Platform mean drift: the platform mean drift should be controlled within a small range, and the drift of platform needs to be monitored in real time, so that the average drift is not more than $S_0 = 43$ m.
(5) Surface current velocity: the surface current velocity should be closely monitored in drilling process. When the monitoring value of $u_w > 1.188\ \mathrm{m\,s^{-1}}$, it is necessary to reduce the top tension of riser in time and appropriately and to control the drift of platform as little as possible, etc.

6 Conclusion

(1) By using methods of dimensionless and sensitivity analysis, the influence of different factors on the characteristic parameters of mechanical stability of subsea wellhead has been analyzed. On this basis, the uncertainty factor that affected the mechanical stability of the instance well subsea wellhead greater and more sensitively was determined—the resistance coefficient.
(2) The uncertainty of resistance coefficient has been integrated into the evaluation of the risk of subsea wellhead instability. And the risk assessment method of subsea wellhead instability considering of uncertain factors in deepwater drilling has been established. It can be used to quantitatively evaluate the risk of subsea wellhead instability in drilling process and determine the monitoring value of drilling parameters and environmental loads to meet the safety requirements for subsea wellhead. Example shows that: according to the selected parameters such as center value of drag coefficient $\mu = 0.8$, fluctuation coefficient of drag coefficient $\sigma = 0.05$, safety limit of subsea wellhead displacement $S_{wm} = 0.37$ m, and safety limit of subsea wellhead deflection angle $\theta_{wm} = 3.1°$, there was 24% probability of occurrence of wellhead instability for target well. Meanwhile, the platform drift S_w should be < 43 m and the maximum marine current velocity u_w should be less than $1.188\ \mathrm{m\,s^{-1}}$.
(3) In this paper, the analysis of the ultimate stress state of subsea wellhead was carried out from the view of statics, and the results represented the limit state of the subsea wellhead system to meet the need of mechanical stability. In future research, dynamic analysis needs to be carried

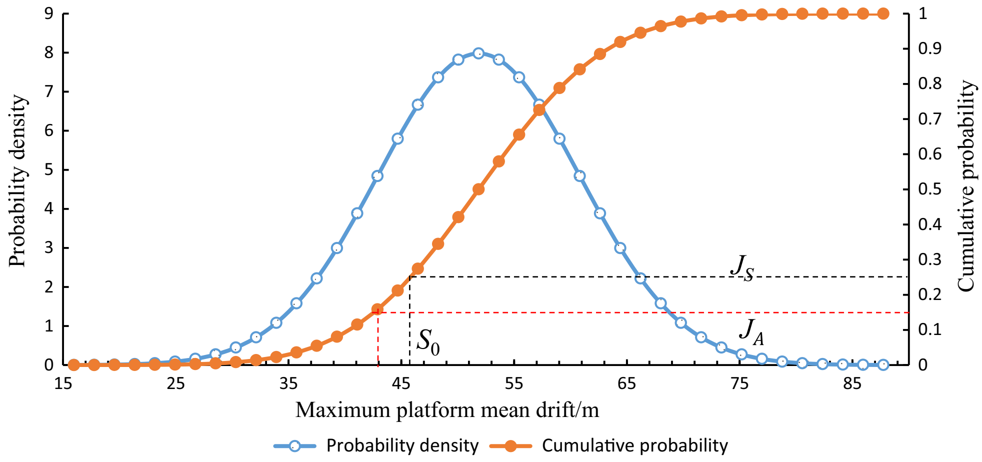

Fig. 8 Probability density and cumulative probability distribution of the maximum platform mean drift of target well

out to analyze the fatigue life of subsea wellhead system, which could further improve the reliability of risk assessment results.

Acknowledgements The authors would like to acknowledge the academic and technical supports of China University of Petroleum (Beijing) and China University of Petroleum (East China). This paper was supported by the National Natural Science Foundation of China (No. 51574275), the National Natural Science Foundation of China (No. 51704320), the National Science Fund for Distinguished Young Scholars (No. 51325402), and Ministry of education innovation team development plan rolling support Project (IRT_14R58).

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