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Multistring analysis of wellhead movement and uncemented casing strength in offshore oil and gas wells

Liu Xiuquan[1], Chen Guoming[1*], Chang Yuanjiang[1], Zhang Lei[1], Zhang Weiguo[2] and Xie Hua[2]

[1] Centre for Offshore Engineering and Safety Technology, China University of Petroleum, Qingdao, Shandong 266580, China
[2] Shenzhen Branch of China Offshore Oil Corporation, Shenzhen, Guangdong 518067, China

Abstract: This paper presents a theoretical method and a finite element method to describe wellhead movement and uncemented casing strength in offshore oil and gas wells. Parameters considered in the theoretical method include operating load during drilling and completion and the temperature field, pressure field and the end effect of pressure during gas production. The finite element method for multistring analysis is developed to simulate random contact between casings. The relevant finite element analysis scheme is also presented according to the actual procedures of drilling, completion and gas production. Finally, field cases are presented and analyzed using the proposed methods. These are four offshore wells in the South China Sea. The calculated wellhead growths during gas production are compared with measured values. The results show that the wellhead subsides during drilling and completion and grows up during gas production. The theoretical and finite element solutions for wellhead growth are in good agreement with measured values and the deviations of calculation are within 10%. The maximum von Mises stress on the uncemented intermediate casing occurs during the running of the oil tube. The maximum von Mises stress on the uncemented production casing, calculated with the theoretical method occurs at removing the blow-out-preventer (BOP) while that calculated with the finite element method occurs at gas production. Finite element solutions for von Mises stress are recommended and the uncemented casings of four wells satisfy strength requirements.

Key words: Offshore oil and gas wells, drilling and completion, gas production, wellhead movement, uncemented casing strength, gap element

1 Introduction

Wellhead assemblies are often installed on platforms in offshore oil and gas wells. A section of casings can not be cemented due to the gap between the platform wellhead and seafloor (Song et al, 2012). The wellhead position and the uncemented casing strength change with operating load and environmental load during drilling, completion and gas production. For example, the wellhead grew up during gas production in a gas field of the South China Sea and the maximum growth reached 0.13 m. Calculation of the wellhead movement is critical for the design of the platform layout and production pipelines around the Christmas tree. Strength assessment of the uncemented casings is important for wellbore integrity (Samuel and Gonzales, 1999; Wu et al, 2008; Xu et al, 2010). However, there is little research on wellhead movement and uncemented casing strength at present. McCabe (1989) was the first to propose a theoretical method for calculating the wellhead movement during drilling and completion. The wellhead movement during drilling and completion in a gas field in the U.K. North Sea was calculated according to the proposed theoretical method and compared with measured values. The result showed that the calculated values were in good agreement with measured data. Then a theoretical method for calculating the wellhead growth during gas production was established considering the temperature field (Aasen and Aadnoy, 2004; 2009; McSpadden and Glover, 2009). However, the influence of the pressure field on wellhead growth during gas production was neglected. In this paper, the theoretical method for calculating the wellhead movement and the uncemented casing strength was improved by including the effect of the pressure field.

Another problem is that the theoretical method mentioned above does not involve random contact between casings on account of its complexity. The finite element method is often

*Corresponding author: email: offshore@126.com
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chosen to analyze contact among strings. Nonlinear springs and gap elements are often adopted to simulate random contact between pipes in finite element models. The nonlinear spring analogue was chosen for simulating random contact between pipes (Bueno and Morooka, 1994; Luk et al, 2009; Yao et al, 2010; Dong et al, 2011). When the gap between pipes is open, the spring stiffness vanishes, while for a closed gap the spring stiffness becomes infinite. Compared with a gap element, the nonlinear spring model often leads to low calculation efficiency and difficulty in convergence (Li, 2002). The gap element model was firstly proposed by Stadter and Weiss (1979). It proved to be efficient in simulating random contact among drillstrings, risers and wellbores (Li, 2002; Liu et al, 2002; Zhang et al, 2002). So the finite element analysis software ABAQUS adopted gap element ITT for random contact simulation between pipes (Chang and Yu, 2003). On the basis of the gap element, a finite element model for calculating wellhead movement and uncemented casing strength is presented in this paper considering random contact between pipes. The relevant finite element analysis scheme is also established according to the actual procedures of drilling, completion and gas production. Finally, the wellhead movement and uncemented casing strength of four wells in the South China Sea are calculated using the proposed methods, and the calculated wellhead growths during gas production are compared with measured values.

2 Mechanical analysis model

Offshore drilling and completion operations mainly include running surface conductor, intermediate casing, production casing, liner, oil tube, installing and removing the BOP, and installing the Christmas tree. Fig. 1 illustrates the wellbore structure after drilling and completion. The whole wellbore comprises wellhead, surface conductor, intermediate casing, production casing, liner and oil tube. The wellhead is installed on the lower deck of platform. The surface conductor and liner are not connected to the wellhead and have no effect on wellhead movement. However, the surface conductor applies a hoop constraint on the wellhead to prevent it from lateral deformation. The surface conductor and the whole wellbore above the mudline are supported laterally by the centralizer structure of platform. The intermediate casing, production casing and oil tube are connected at the wellhead as a multi-string system which determines the wellhead movement. The intermediate casing and production casing consist of the lower cemented part and the upper uncemented part. The cemented casings are consolidated with soil by the cement sheath and cannot move axially. So the cemented casings have no influence on the wellhead movement. It is the uncemented casings that determine the wellhead movement. So this paper focuses on the mechanical analysis of the uncemented intermediate casing, uncemented production casing and the oil tube. The mechanical analysis model for wellhead movement and uncemented casing strength shown in Fig. 2 was established according to the actual load conditions of uncemented casings.

Fig. 2 shows that loads acting on the uncemented casings and the oil tube include the temperature and pressure fields, axial force and contact load between casings. The

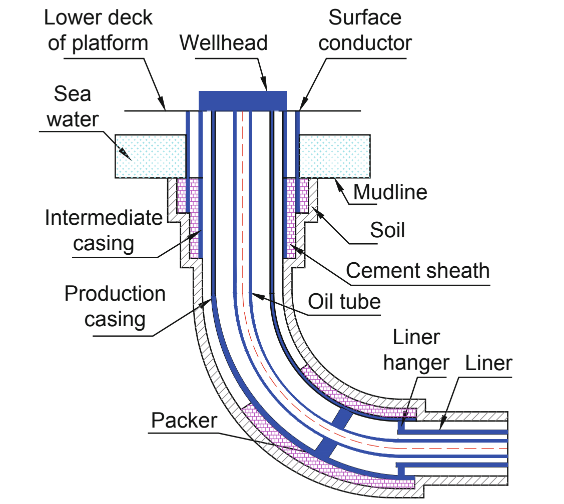

Fig. 1 Well structure diagram of offshore oil and gas wells

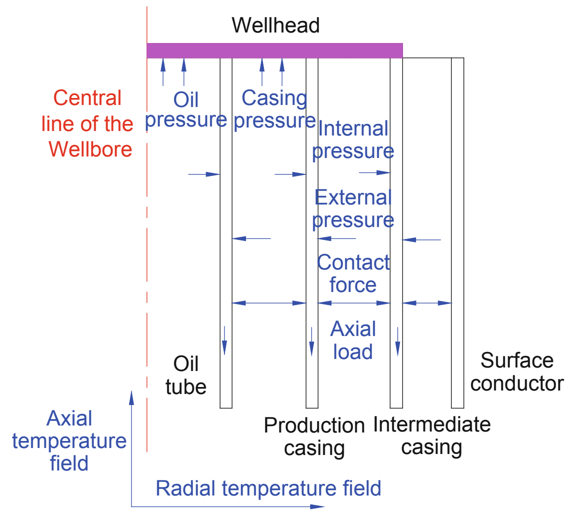

Fig. 2 Mechanical analysis model for wellhead movement and uncemented casing strength

temperature and pressure fields can be obtained from actual measurements while the axial load and contact load between casings should be calculated. The following theoretical method will describe the details of the calculation process of the axial load during drilling, completion and gas production. The wellhead movement and the uncemented casing strength are then assessed based on the calculated axial load. The whole procedures of drilling, completion and gas production are simulated using the finite element method. The wellhead movement and the uncemented casing strength can be determined directly from the finite element analysis.

3 Theoretical method

3.1 Calculation of wellhead movement and casing axial load during drilling and completion

The axial stiffness of each casing is defined as

$$K_i = \frac{EA_i}{L_{i,\text{vertical}}} \tag{1}$$

where K_i is the axial stiffness of the ith casing, N/m; E is the elastic modulus, Pa; A_i is the cross sectional area of the ith casing, m^2; $L_{i,\text{vertical}}$ is the vertical component of the uncemented length of the ith casing, m.

The multi-string system is taken as parallel springs when the intermediate casing, production casing and the oil tube are connected at the wellhead. The axial stiffness of the multistring system is given by

$$K_{j,\mathrm{sys}}=\sum_{i=1}^{N_j}K_i=\sum_{i=1}^{N_j}\frac{EA_i}{L_{i,\mathrm{vertical}}} \tag{2}$$

where $K_{j,\mathrm{sys}}$ is the axial stiffness of the multi-string system during the jth operation, N/m; N_j is the number of casings related to the wellhead movement during the jth operation.

The wellhead movement during each operation is written as

$$\Delta z_j=\frac{W_j}{K_{j,\mathrm{sys}}}=\frac{W_j}{\sum_{i=1}^{N_j}\frac{EA_i}{L_{i,\mathrm{vertical}}}} \tag{3}$$

where Δz_j is the wellhead movement during the jth operation, m; W_j is the jth operating load, N.

The variation of axial load on the casing during each operation is written as

$$\Delta F_{i,j}=\frac{K_i}{K_{j,\mathrm{sys}}}W_j=\frac{\frac{A_i}{L_{i,\mathrm{vertical}}}}{\sum_{i=1}^{N_j}\frac{A_i}{L_{i,\mathrm{vertical}}}}W_j \tag{4}$$

where $\Delta F_{i,j}$ is the variation of axial load on the ith casing head during the jth operation, N.

The axial load on each casing head after drilling and completion is given by

$$\Delta F_{i,\mathrm{d}}=\sum_{j=1}^{n}\Delta F_{i,j} \tag{5}$$

where $\Delta F_{i,\mathrm{d}}$ is the variation of axial load on the ith casing head after drilling and completion, N; n is the total number of operations during drilling and completion.

3.2 Calculation of wellhead movement and axial load on the casing during gas production

The origin of coordinates is at the wellhead, and the z axis is along the well track. The axial deformation of each casing due to wellbore temperature field is given as (Maharaj, 1996; McSpadden and Glover, 2008; Yan et al, 2010)

$$\Delta l_{i,\mathrm{t}}=\int_0^{L_i}\alpha\Delta t_i(z)\,\mathrm{d}z \tag{6}$$

where $\Delta l_{i,\mathrm{t}}$ is the axial deformation of the ith casing due to the wellbore temperature field, m; L_i is the uncemented length of the ith casing, m; α is the linear expansion coefficient of casings, ºC^{-1}; $\Delta t_i(z)$ is the temperature variation of the ith casing at z during gas production, ºC.

The axial deformation of each casing due to the wellbore pressure field is expressed as

$$\Delta l_{i,\mathrm{p}}=\int_0^{L_i}2\mu\frac{D_i^2\Delta p_{i2}(z)-d_i^2\Delta p_{i1}(z)}{E(D_i^2-d_i^2)}\,\mathrm{d}z \tag{7}$$

where $\Delta l_{i,\mathrm{p}}$ is the axial deformation of the ith casing due to wellbore pressure field, m; μ is the Poisson ratio; d_i is the inner diameter of the ith casing, m; D_i is the outer diameter of the ith casing, m; $\Delta p_{i1}(z)$ is the internal pressure variation of the ith casing at z during gas production, Pa; $\Delta p_{i2}(z)$ is the external pressure variation of the ith casing at z during gas production, Pa.

Then the axial load on the wellhead due to the casing axial deformation is expressed as

$$F_{\mathrm{tp}}=\sum_{i=1}^{N}EA_i\frac{\Delta l_{i,\mathrm{t}}+\Delta l_{i,\mathrm{p}}}{L_{i,\mathrm{vertical}}}=\sum_{i=1}^{N}EA_i\frac{\int_0^{L_i}[\alpha t_i(z)+2\mu\frac{D_i^2\Delta p_{i2}(z)-d_i^2\Delta p_{i1}(z)}{E(D_i^2-d_i^2)}]\,\mathrm{d}z}{L_{i,\mathrm{vertical}}} \tag{8}$$

where F_{tp} is the axial load on the wellhead, N; N is the total number of casings related to the wellhead movement.

The casing pressure and oil pressure are zero during drilling and completion. However, they increase during gas production and impose load on the wellhead. The wellhead load due to the end effect of casing pressure and oil pressure is given by

$$F_{\mathrm{end}}=\pi r_{\mathrm{tube}}^2p_{\mathrm{tube}}+\pi(r_{\mathrm{casing2}}^2-R_{\mathrm{tube}}^2)p_{\mathrm{casing}} \tag{9}$$

where F_{end} is the wellhead load due to the end effect of pressure, N; r_{tube} is the inner diameter of the oil tube, m; p_{tube} is the oil pressure, Pa; r_{casing2} is the inner diameter of the production casing, m; R_{tube} is the outer diameter of the tube, m; p_{casing} is the casing pressure, Pa.

According to the calculated wellhead load due to the temperature field, pressure field and the end effect of casing pressure and oil pressure, the wellhead movement during gas production is written as

$$\Delta z_{\mathrm{p}}=\frac{F_{\mathrm{tp}}+F_{\mathrm{end}}}{K_{\mathrm{sys}}}=\frac{F_{\mathrm{tp}}+F_{\mathrm{end}}}{\sum_{i=1}^{N}\frac{EA_i}{L_{i,\mathrm{vertical}}}} \tag{10}$$

where Δz_{p} is the wellhead movement during gas production, m; K_{sys} is the axial stiffness of the multistring system, N/m.

The axial load variation of each casing during gas production is written as

$$\Delta F_{i,\mathrm{p}}=K_i(\Delta z_{\mathrm{p}}-\Delta l_{i,\mathrm{t}}-\Delta l_{i,\mathrm{p}})=\frac{EA_i}{L_{i,\mathrm{vertical}}}(\Delta z_{\mathrm{p}}-\Delta l_{i,\mathrm{t}}-\Delta l_{i,\mathrm{p}}) \tag{11}$$

where $\Delta F_{i,\mathrm{p}}$ is the axial load variation of the ith casing during gas production, N.

The axial load on each casing head after drilling, completion and gas production is given by

$$F_i=\Delta F_{i,\mathrm{d}}+\Delta F_{i,\mathrm{p}} \tag{12}$$

where F_i is the axial load on the ith casing head, N.
The axial load on each casing at z is written as

$$F_i(z)=F_i-\int_0^z W_i(z)\,\mathrm{d}z \tag{13}$$

where $F_i(z)$ is the axial load on the ith casing at z, N; $W_i(z)$ is the unit weight of the ith casing at z, N/m.

3.3 Strength assessment of uncemented casings

The axial stress on the casing, radial stress and hoop stress can be calculated by the following equations according to the measured pressure and calculated axial force (Tan and Gao, 2005; Wu and Knauss, 2006; wu et al, 2008).

$$\sigma_\mathrm{a} = \frac{4F}{\pi(D^2 - d^2)} \tag{14}$$

$$\sigma_\mathrm{r} = \frac{D^2 d^2}{D^2 - d^2}\frac{p_2 - p_1}{4r^2} + \frac{d^2 p_1 - D^2 p_2}{D^2 - d^2} \tag{15}$$

$$\sigma_\theta = -\frac{D^2 d^2}{D^2 - d^2}\frac{p_2 - p_1}{4r^2} + \frac{d^2 p_1 - D^2 p_2}{D^2 - d^2} \tag{16}$$

where σ_a is the axial stress on casings, Pa; σ_r is the radial stress, Pa; σ_θ is the hoop stress, Pa; D is the outer diameter of casings, m; d is the inner diameter of casings, m; F is the axial load on casings, N; r is the distance between the calculation point and the casing center, m; p_2 is the external pressure on casings, Pa; p_1 is the internal pressure on casings, Pa.

As the axial stress, radial stress and hoop stress on casings are obtained, the von Mises stress S_eff on the casing is written as

$$S_\mathrm{eff} = \sqrt{\frac{1}{2}[(\sigma_\mathrm{a} - \sigma_\mathrm{r})^2 + (\sigma_\mathrm{a} - \sigma_\theta)^2 + (\sigma_\mathrm{r} - \sigma_\theta)^2]} \tag{17}$$

4 Finite element method

4.1 Basic equations

The stiffness matrix and external load column vector can be determined based on the wellbore structure and the operating load in finite element analysis. However, the random contact force between casings is complex and can not be determined directly. The contact force between casings is written as

$$\begin{cases} r_i = 0 & g_i^1 < g_i^0 \\ r_i > 0 & g_i^1 = g_i^0 \end{cases} \tag{18}$$

where r_i is the contact force of the ith contact pair, N; g_i^0 is the inertial gap of the ith contact pair, m; g_i^1 is the gap after deformation, m.

ABAQUS/Standard is used to solve inequalities of contact force. Beam element PIPE31 is adopted to simulate casings. Contact element ITT31 is adopted to simulate random contact between casings.

4.2 Solution process

The wellhead movement and uncemented casing strength during each operation should be calculated since the wellbore structure and the operating load always change during drilling, completion and gas production. The finite element analysis scheme shown in Fig. 3 is established according to the actual procedures of drilling, completion and gas production. The internal and external pressure on each casing is applied by DLOAD command in ABAQUS.

5 Case study

5.1 Calculation parameters

The wellhead movement and the uncemented casing strength of four gas wells in the South China Sea were calculated with the proposed methods. The water depth was 198 m and the temperature was 20 ºC. The formation temperature gradient was 4.08 ºC/100 m. The weight of BOP and Christmas tree were 50 tonnes and 6.6 tonnes respectively. Detailed parameters of each casing are listed in Table 1. Wellbore structures are listed in Table 2. The temperature and pressure fields are listed in Table 3. The detailed temperature fields of the uncemented casings and the oil tube of well A01H are shown in Fig. 4.

Table 1 Detailed parameters of each casing

Pipe	Outer diameter m	Inner diameter m	Unit weight kg/m	Material	Yield strength MPa
Surface conductor	0.610	0.546	363.5	X56	386
Intermediate casing	0.340	0.315	100.6	N80	552
Production casing	0.244	0.220	69.6	L80	552
Oil tube	0.114	0.100	18.6	L80	552

Table 2 Wellbore structure

Well	The length of the oil tube, m	The length of the production casing, m	The length of the uncemented production casing, m	The length of the intermediate casing, m	The length of the uncemented intermediate casing, m	The length of the surface conductor, m
A01H	4470	3975	935	1120.0	253.86	383.8
A02H	5400	5038	905	1048.2	253.86	411.0
A03H	4410	4009	883	1091.2	253.86	395.8
A04H	5560	5094	1022	1344.3	253.86	386.6

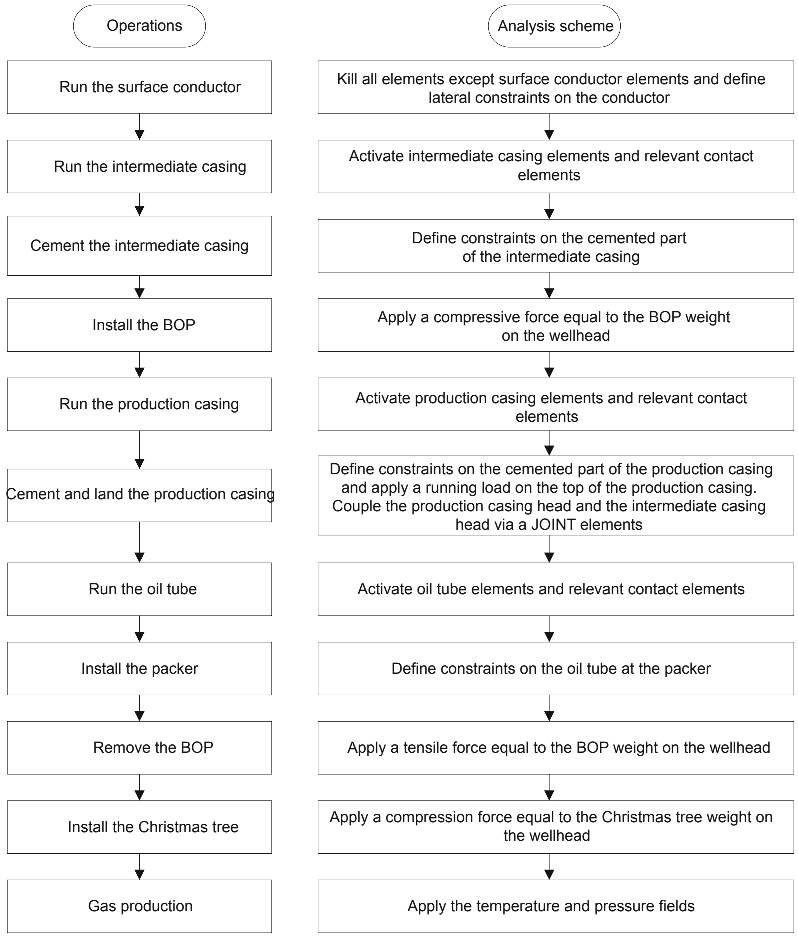

Fig. 3 Finite element analysis scheme

Table 3 Wellbore temperature and pressure fields

Well	Bottom hole temperature, ºC	Wellhead temperature, ºC	Bottom hole pressure, MPa	Oil pressure, MPa	Casing pressure, MPa
A01H	125	99.4	30.5	20.4	0
A02H	124	80.7	29.2	20.7	0
A03H	95	54.9	21.5	15.5	0
A04H	82	59.1	18.3	13.3	1.2

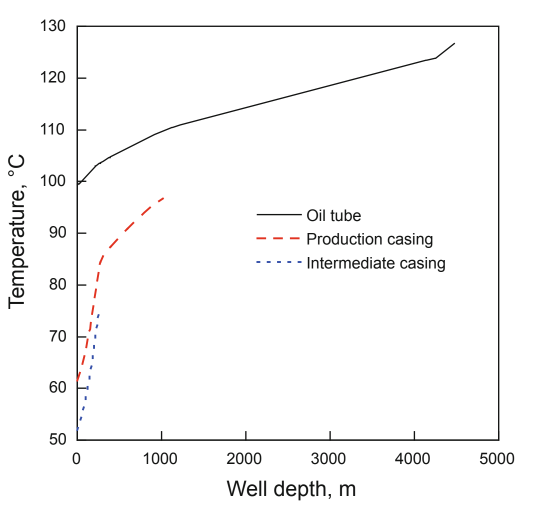

Fig. 4 The detailed temperature fields of uncemented casings and oil tube in well A01H

5.2 Mechanical characteristics of the multistring system

Mechanical characteristics of the multistring system were analyzed with the proposed finite element method, which can simulate the random contact between casings. The production casing was chosen considering that the uncemented part of the production casing was long and makes the primary contribution to the wellhead movement. The contact load on the uncemented production casing in well A01H is shown in Fig. 5.

Fig. 5 shows that the contact load between the uncemented production casing and the intermediate casing is low in the vertical section and hold section while the contact load is high in the build section. The maximum value of the contact load is needed for the production casing to bend in order to adapt to the deflecting well track.

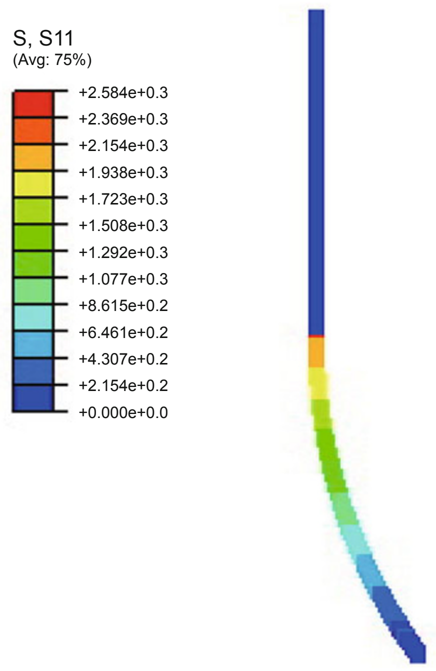

Fig. 5 Contact load on the uncemented production casing

5.3 Calculation of the wellhead movement

On the basis of methods proposed in this paper, the wellhead movement was calculated for four gas wells of Panyu gas field in the South China Sea. The calculated wellhead movement of well A01H is shown in Fig. 6. Operations from 1 to 7 in Fig. 6 stand for running the intermediate casing, installing the BOP, running the production casing, running the oil tube, removing the BOP, installing the Christmas tree, and gas production respectively.

Fig. 6 shows that the theoretical solution is close to the finite element solution. The wellhead subsides during drilling and completion due to the weight of the production casing, oil tube and the Christmas tree. The maximum wellhead subsidence is about 0.15 m. The wellhead rises during gas production due to the variations of temperature and pressure fields. The calculated wellhead movement during drilling and completion proved to be in good agreement with measured values by McCabe (1989) in the North Sea gas field. The comparisons between the calculated wellhead growths and measured values during gas production are listed in Table 4.

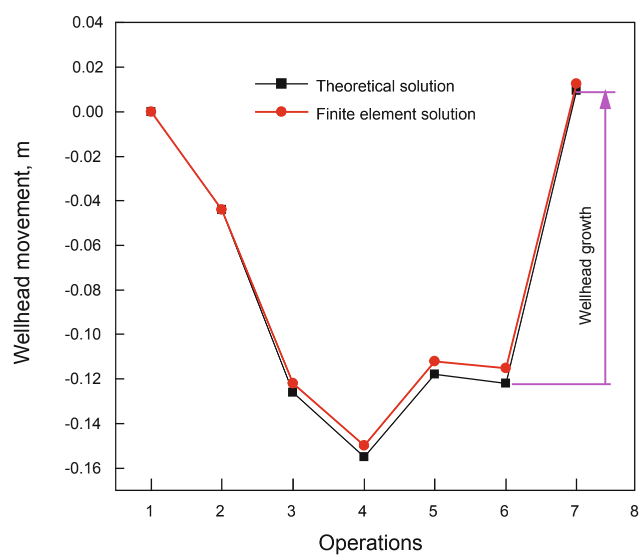

Fig. 6 Calculated wellhead movement of well A01H

Table 4 Comparison between calculated wellhead growths and measured data

Well	Measured data, m	Theoretical solution, m	The deviation of theoretical solution, %	Finite element solution, m	The deviation of finite element solution, %
A01H	0.125	0.132	5.8	0.128	2.4
A02H	0.105	0.115	9.2	0.103	-1.8
A03H	0.065	0.064	-0.2	0.059	-9.74
A04H	0.05	0.053	6.7	0.046	-7.56

Table 4 shows that the wellhead growths during gas production are from 0.05 to 0.13 m. The theoretical and finite element solutions for wellhead growth are in good agreement with the measured values and the deviations of calculation are within 10%. The finite element solutions are smaller than the theoretical solutions because the interaction between casings is taken into consideration in the finite element model.

The temperature and pressure fields are two factors governing the wellhead growth. The pressure field includes oil pressure and casing pressure, and the casing pressure is essentially constant during gas production. So the influence of wellhead temperature and oil pressure on the wellhead growth of well A01H is calculated, as shown in Figs. 7 and 8.

Figs. 7 and 8 show that the wellhead growth increases with the wellhead temperature and oil pressure. Compared with the oil pressure, the wellhead temperature has greater influence on the wellhead growth.

5.4 Strength assessment of the uncemented casings

The axial load on each casing should be calculated before assessing the strength of the uncemented casings. Fig. 9 illustrates the calculated axial loads on the intermediate and production casings in well A01H. Operations from 1 to 7 in Fig. 9 stand for running the intermediate casing, installing the BOP, running the production casing, running the oil tube, removing the BOP, installing the Christmas tree, and gas production respectively.

Fig. 9 shows that the theoretical solutions are similar to the finite element solutions for the casing axial load. The intermediate casing head is under compression all the time and the maximum compressive load occurs at running the oil tube. The production casing head is under tension during

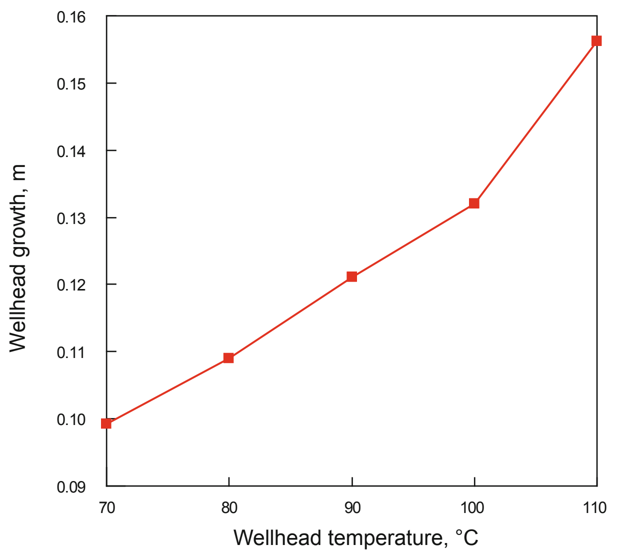

Fig. 7 The influence of the wellhead temperature on the wellhead growth

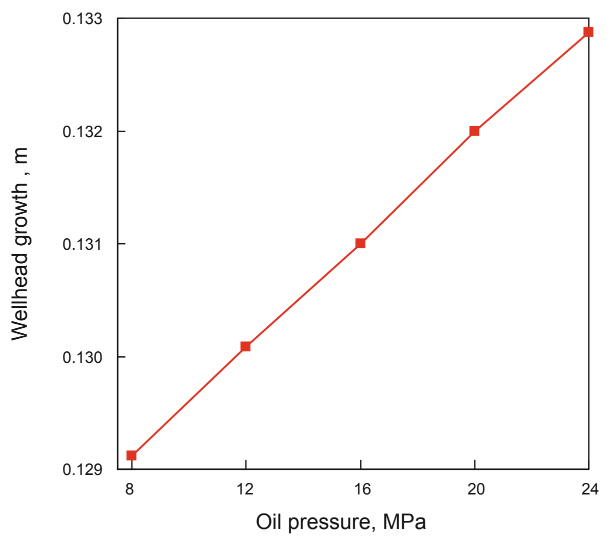

Fig. 8 The influence of the oil pressure on the wellhead growth

drilling and completion and under compression during gas production. The maximum tensile load on the production casing occurs at removing the BOP. Von Mises stresses on the uncemented casings during different operations, shown in Fig. 10, were calculated according to the axial load on each casing.

Fig. 10 shows that the maximum von Mises stress on the intermediate casing occurs at running the oil tube because the axial compressive force is highest at this time (as shown in Fig. 9). The maximum von Mises stress on the production casing calculated with the theoretical method occurs at removing the BOP while that maximum value calculated with the finite element method occurs at the stage of gas production. The production casing head is under compression during gas production, and the uncemented production casing is so long that the bottom of the production casing bends. However, the casing bending is not considered in the theoretical method, so the difference between the von Mises stresses on the production casings calculated with two methods is large. For safety consideration, the finite element

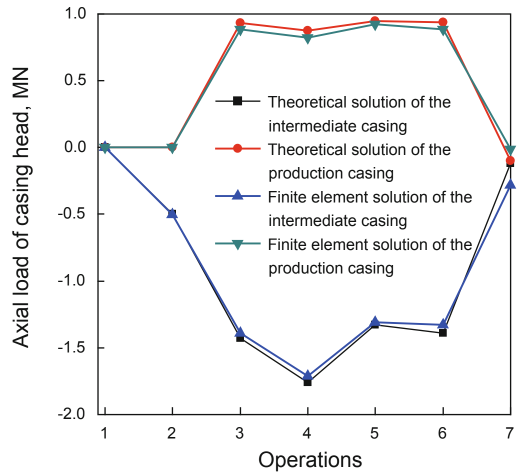

Fig. 9 Calculated axial loads on each casing head during different operations

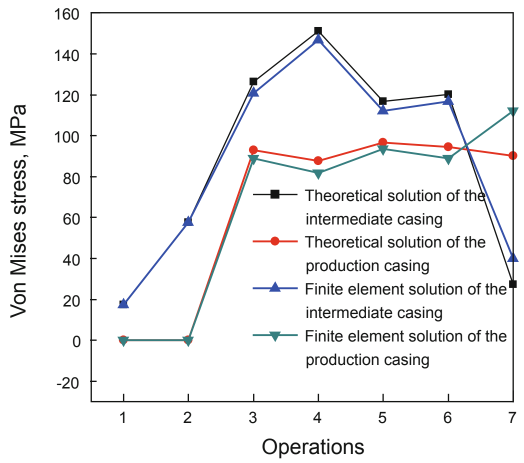

Fig. 10 Von Mises stresses during different operations

solutions for von Mises stress are recommended. Table 5 lists the calculated strength of the uncemented casings in four wells. The result shows that all the uncemented casings satisfy strength requirements. Every uncemented casing keeps structural integrity during drilling, completion and gas production.

Table 5 The calculated strengths of uncemented casings

Well	Pipe	Material	Minimum yield strength MPa	Maximum von Mises stress MPa	Safety factor
A01H	Intermediate casing	N80	552	151	3.7
	Production casing	L80	552	112	4.9
A02H	Intermediate casing	N80	552	139	4.0
	Production casing	L80	552	96	5.8
A03H	Intermediate casing	N80	552	140	4.0
	Production casing	L80	552	100	5.5
A04H	Intermediate casing	N80	552	148	3.7
	Production casing	L80	552	112	4.9

6 Conclusions

1) A theoretical method and a finite element method for calculating wellhead movement and uncemented casing strength are proposed in this paper. Compared with the existing theoretical method, the proposed theoretical method considered the influence of pressure field and its effect on the wellhead movement and the uncemented casing strength during gas production. On the basis of the gap element model, a finite element method for multistring analysis was presented to simulate random contact between casings. The relevant finite element analysis scheme was also presented according to the actual procedures of drilling, completion and gas production.

2) The wellhead subsides during drilling and completion and the maximum wellhead subsidence is about 0.15 m. The wellhead rise during gas production is between 0.05 m and 0.13 m. The theoretical and finite element solutions for wellhead growth are in good agreement with measured values and the deviations of calculation are within 10%.

3) The theoretical solutions are similar to the finite element solutions for the axial load on casings. The intermediate casing head is under compression all the time and the maximum compressive load occurs at the running of the oil tube. The production casing head is under tension during drilling and completion and under compression during gas production. The maximum tensile load on the production casing occurs on the removal of the BOP.

4) Von Mises stresses on the uncemented casings change during drilling, completion and gas production. The maximum von Mises stress on the intermediate casing occurs during the running of the oil tube. The maximum von Mises stress on the production casing calculated with the theoretical method occurs on removing the BOP while that calculated with the finite element method occurs at gas production. For safety consideration, the finite element solutions for von Mises stress are recommended. Uncemented casings of the four wells in China South Sea satisfy strength requirements.

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