Research Article

Integrity Evaluation of Cement Ring during Fracturing and Flowback of Horizontal Well in Jimsar Shale Oil

Hu Yang,1 Penggao Zhou,2 Chao Xiong,3 Shifu Yu,4 and Jiancai Li5

1China University of Petroleum (Beijing), Karamay, Xinjiang 834000, China
2Karamay Vocational & Technical College, Karamay, Xinjiang 834000, China
3Engineering Technology Research Institute, Xinjiang Oilfield Company, PetroChina, Karamay, Xinjiang 834000, China
4Research Institute of Oil and Gas Technology, Changqing Oilfield Company, CNPC, Xi’an, Shanxi 710018, China
5Jiqing Field Operation District of Xinjiang Oilfield Company, CNPC, Jimsar, Xinjiang 831700, China

Correspondence should be addressed to Hu Yang; 1250964233@qq.com

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Horizontal well volume fracturing has become the main technology for effective development of unconventional oil and gas. In the process of fracturing and flowback of horizontal wells, the changes of wellbore temperature and pressure will affect the magnitude and distribution of stress in cement sheath, which may lead to compression or tensile failure of cement sheath, or a microclearance between casing and cement sheath. Therefore, based on the elastic theory of thick-walled cylinder, the elastic model of casing cement sheath and formation combination is established, and the finite difference program FLAC3D (Fast Lagrangian Analysis of Continua in Three-Dimensional) was used to solve the model. The simulation evaluation of several horizontal wells in Jimsar shale oil shows that the main failure mode of cement sheath in horizontal well section is radial compression or circumferential tensile failure in fracturing period, and the main failure mode is a microclearance failure in flowback period. Taking Jimsar shale oil horizontal well JHW00421 as an example, the critical values of wellbore pressure and mechanical parameters of cement when cement sheath fails during fracturing flowback and their relationship are predicted or evaluated. The findings of this study are helpful to better understand and evaluate how different fracturing or flowback operation parameters affect the integrity of cement sheath and the effectiveness of interlayer sealing in horizontal well sections.

1. Introduction

Generally, after cementing slurry solidifies in long horizontal shale oil wells, the casing is subjected to wellbore fluid pressure while the formation rock outside the cement ring is subjected to in situ stress. In the process of fracturing fluid pressure modification, fluid pressure in the casing increases, leading to casing expansion and stress concentration around the perforation, which may lead to compression failure or tensile failure of the cement ring body, thus causing the cement ring to lose its function of sealing the formation and casing [1–4]. In the process of liquid flowback after fracturing, the fluid pressure in the casing decreases and the casing shrinks, which may lead to the microclearance between the casing and the cement ring, leading to the failure of the first and second interfaces [3–6]. Therefore, it is important to consider changes in wellbore temperature and pressure during production in the analysis of cement stress to predict cement ring integrity and zonal isolation effectiveness.

In recent years, many scholars have conducted in-depth research on the mechanical integrity of cementing cement sheath. Bosma [4] established the finite element mechanical model of casing cement sheath formation combination on Diana finite element software; analyzed various failure forms such as tension, shear, and interface separation; and applied the research results to natural gas wells and gas storage wells. Li et al. [5] established the physical and mechanical model of casing cement sheath wellbore surrounding rock combination according to the thick wall cylinder theory and carried out the elastic-plastic mechanical analysis of the combination under the action of uniform in-situ stress. Chen et al.
At present, most of the world’s unconventional oil and gas development model is the long-term horizontal well volume fracturing. During large-scale volume fracturing, the formation pressure increases from the original reservoir pressure to the fracturing injection pressure, and the formation pressure gradually decreases with fracturing fluid flowback during flowback. Therefore, it is very important to establish the stress distribution of cement ring under the condition of uniform in situ stress by adopting the elastic mechanics of thick wall cylinder assembly.

2.1. Assumptions. The casing is linearly elastic and does not produce yield failure downhole. The formation is homogeneous, isotropic, and linearly elastic, and the borehole wall is stable and smooth cylinder. The annular cement ring has no gap, the volume of cement does not change during setting, and the casing/cement ring and cement ring/formation interface bond well before the wellbore load is applied. The casing/cement ring/formation complex keeps balance under wellbore load; after the cement slurry is completely set into the cement ring, the in situ stress is completely loaded on the cement ring [5–11].

Since the mechanical model of casing/cement ring/formation assembly is axisymmetric, the physical and mechanical model is a plane strain problem in the polar coordinate system (Figure 1). The relevant variables include radial displacement, radial stress, circumferential stress, and shear stress [12–17]. Among them, the inner surface of the casing bears the radial stress caused by the increase of wellbore temperature and pressure caused by wellbore fluid. The outer surface of the outer stratum rock bears the action of the ground stress; The middle section is the cement ring of greatest concern, where the inner and outer surfaces are subjected to a combination of casing and formation forces.

During mechanical analysis, the temperature in the wellbore is $T_i$, and the ground temperature $T_f$ remains unchanged. Assuming that the thermal conductivity of the casing is good and that the heat loss between the inner and outer surfaces of the casing is negligible, the temperature of the outer surface of the casing is also.

In the whole cement consolidation system, the temperature
distribution along the radial direction of the cement ring [12] is

\[ T = T_i - (T_i - T_r) \ln \left( \frac{R}{R_b} \right), \]

where \( R \) is the distance between the cement ring and the wellbore center, \( m \); \( R_b \) is the radius of inner surface of cement ring, \( m \); and \( R_c \) is the radius of outer surface of cement ring, \( m \).

2.2. Constitutive Equation. According to the elastic theory of composite thick-walled cylinder, it is assumed to be a plane strain problem, and the strain variable in the \( z \) direction is 0. Therefore, the radial and circumferential stresses of thick-walled cylinders must meet the balanced relationship [2]:

\[ \frac{dr}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0. \]

Therefore, the constitutive equation of composite thick-walled cylinder assembly is as follows:

\[ \begin{align*}
\varepsilon_r &= \frac{1}{E} \left[ (1 - \mu^2) \sigma_r - (\mu + \mu^2) \sigma_\theta + (1 + \mu) \alpha E T \right] \\
\varepsilon_\theta &= \frac{1}{E} \left[ (1 - \mu^2) \sigma_\theta - (\mu + \mu^2) \sigma_r + (1 + \mu) \alpha E T \right],
\end{align*} \]

where \( \alpha \) is the thermal expansion coefficient of the material, \( m/K \); \( E \) is the elastic modulus of the material, \( Pa \); \( \mu \) is the Poisson’s ratio of the material, dimensionless; \( \varepsilon_r \) is the radial strain of thick-walled cylinder, dimensionless; \( \varepsilon_\theta \) is the circumferential strain of thick-walled cylinder, dimensionless; \( \varepsilon_t \) is the axial strain of thick-walled cylinder, dimensionless; \( \sigma_r \) is the radial stress of thick-walled cylinder, \( Pa \); \( \sigma_\theta \) is the circumferential stress of thick-walled cylinder, \( Pa \); and \( \sigma_z \) is the axial stress of thick-walled cylinder, \( Pa \).

2.3. Stress Equation. According to the elastic mechanics theory of thick-walled cylinder and the principle of stress superposition, the compressive stress inside and outside the cement ring is regarded as the internal stress vector sum generated by two external forces acting on the cement ring separately [18–20]. Figure 2 shows the radial and circumferential stress distribution of cementing cement ring under internal and external pressures.

According to the geometrical and mechanical conditions of the cement ring boundary, the radial, circumferential, and axial stresses and the maximum shear stresses on the cement ring can be obtained (Equation (4)).

\[ \begin{align*}
\sigma_r^{\text{cement}} &= P_{c1} \frac{R_b^2}{R_c^2 - R_b^2} \left( 1 - \frac{R^2}{R_c^2} \right) - P_{c2} \frac{R_b^2}{R_b^2 - R_c^2} \left( 1 - \frac{R_b^2}{R_c^2} \right), \\
\sigma_\theta^{\text{cement}} &= P_{c1} \frac{R_b^2}{R_c^2 - R_b^2} \left( 1 + \frac{R^2}{R_c^2} \right) - P_{c2} \frac{R_b^2}{R_b^2 - R_c^2} \left( 1 + \frac{R_b^2}{R_c^2} \right), \\
\tau_{\max} &= \left( P_{c1} - P_{c2} \right) \frac{R_b^2}{R_c^2 - R_b^2} \frac{1}{r^2}. \end{align*} \]

2.4. Boundary Displacement Equation. By substituting Equation (3) into Equation (2) and integrating, the displacement equation of thick-walled cylinder assembly can be obtained:

\[ \begin{align*}
\varepsilon_r &= \frac{d\delta}{dr} = \frac{1}{1 - \mu} \left( 1 + \mu \right) \alpha E T \int_{r_1}^{r_2} Trdr + C_1 - C_2, \\
\varepsilon_\theta &= \frac{\delta}{r} = \frac{1}{1 - \mu} \alpha \int_{r_1}^{r_2} Trdr + C_1 + C_2 r^2,
\end{align*} \]

where \( \delta \) is the radial displacement of the thick-walled cylinder, \( m \); \( r_i \) is the inner surface radius of the thick-walled cylinder, \( m \); and \( C_1 \) and \( C_2 \) are the integral constant.

According to the boundary geometrical conditions of the composite body and the strain-constitutive equation, the radial displacement equation of each boundary of the thick wall cylinder composite body with cement ring is obtained:

(1) The outer surface of casing

\[ \delta_{r=R_b}^{\text{ax}} = \frac{R_b}{E_v} \left( P_{c1} \frac{R_c^2 + R_b^2}{R_c^2 - R_b^2} - P_{c2} \frac{2R_b^2}{R_b^2 - R_c^2} + P_{c1} \left( \mu_r + \mu_\theta \right) + (1 + \mu_r) R_b \alpha_r T \right) \]

(2) Inner surface of cement ring

\[ \delta_{r=R_b}^{\text{ax}} = \frac{R_b}{E_v} \left( 1 - \mu_r \right) \left( P_{c1} \frac{R_b^2 + R_c^2}{R_c^2 - R_b^2} - P_{c2} \frac{2R_b^2}{R_b^2 - R_c^2} \right) + P_{c1} \left( \mu_r + \mu_\theta \right) + (1 + \mu_r) R_b \alpha_r T \]
The outer surface of the cement ring
\[ \delta_{\text{cement}}^{	ext{r}} = \frac{R_i}{E_c} \left\{ (1 - \mu_c^2) \left[ P_{c1} \left( \frac{2R_b^2}{R_c^2 - R_b^2} \right) - P_{c2} \left( \frac{R_c^2 + R_b^2}{R_c^2 - R_b^2} \right) \right] 
+ P_{c2} (\mu_c + \mu_i^2) \right\} + (1 + \mu_i) R_i \alpha_s T \]

(8)

The inner surface
\[ \delta_{\text{formation}}^{	ext{r}} = \frac{R_i}{E_f} \left\{ (1 - \mu_f^2) \left[ P_{c2} \left( \frac{R_b^2 + R_c^2}{R_b^2 - R_c^2} \right) - P_{c1} \left( \frac{2R_b^2}{R_b^2 - R_c^2} \right) \right] 
+ P_{c1} (\mu_f + \mu_i^2) \right\} + (1 + \mu_i) R_i \alpha_f T \]

(9)

where \( E_s, E_c, \) and \( E_f \) are, respectively, the elastic modulus of casing, cement stone, and formation rock, Pa; \( \mu_s, \mu_c, \) and \( \mu_f \) are, respectively, the Poisson’s ratio of casing, cement stone, and formation rock, dimensionless; \( \alpha_s, \alpha_c, \) and \( \alpha_f \) are, respectively, the thermal expansion coefficient of casing, cement stone, and formation rock, \( \text{m/K} \). \( P_{c1} \) is cement ring/formation interface pressure, Pa; \( R_i \) is the outer radius of the casing. 

Figure 3: Failure modes of cement sheath under internal and external pressure. (a) Compression failure. (b) Tensile failure. (c) Cementation destroy.

Figure 4: Mechanical test photo of cementing stone in Jimsar shale oil layer.

Figure 5: Stress-strain test curve of cementing cement stone in Jimsar shale oil reservoir.
of cement ring, m. \( P_i \) is the casing pressure, Pa; \( P_{cl} \) is the interface pressure of casing/cement ring, Pa; \( R_i \) is the inner radius of casing, m; \( R_b \) is the outer radius of casing, m; \( R_d \) is the oil and gas discharge radius that maintains original pressure of the reservoir, m; \( t \) is the casing thickness, m.

If the cement ring is well cemented, and the radial deformation of casing, cement ring, and formation is in a continuous state, its radial displacement should meet the following requirements:

\[
\left\{ \begin{array}{ll}
\delta_{r=R_b}^\text{cement} = \delta_{r=R_b}^\text{cement} \\
\delta_{r=R_i}^\text{formation} = \delta_{r=R_i}^\text{formation}
\end{array} \right.
\]

Thus, radial, circumferential, and axial stresses and the maximum shear stresses on the cement ring are obtained (Equation (11)). Figure 2 shows the distribution law of radial and circumferential stresses on the cement ring under the action of internal and external pressures.

\[
\sigma_r = P_{cl} \frac{R_b^2}{R_i^2 - R_b^2} \left( 1 - \frac{R_i^2}{r^2} \right) - P_{cl} \frac{R_i^2}{R_i^2 - R_b^2} \left( 1 - \frac{R_b^2}{r^2} \right),
\]

\[
\sigma_\theta = P_{cl} \frac{R_b^2}{R_i^2 - R_b^2} \left( 1 + \frac{R_i^2}{r^2} \right) - P_{cl} \frac{R_i^2}{R_i^2 - R_b^2} \left( 1 + \frac{R_b^2}{r^2} \right),
\]

\[
\sigma_z = \mu (\sigma_r - \sigma_\theta) - \sigma_z E_t T,
\]

\[
\tau_{\text{max}} = \frac{(P_{cl} - P_{cl}) R_b^2 R_i^2}{R_i^2 - R_b^2} \frac{1}{r^2}.
\]

### 3. Failure Pattern of Cement Ring

In general, after the cement slurry has set, the casing is subjected to internal pressure due to the wellbore fluid, and the formation rock outside the cement ring is subjected to in situ stress. The fluid pressure in the casing increases during fracturing, leading to casing expansion, which may lead to compression failure or tensile failure of the cement ring. During fracturing fluid flowback or production, the fluid pressure in the casing decreases and the casing shrinks, which may lead to microclearance between the casing and the cement ring, i.e., cement failure.

If, during fracturing of a horizontal well, the elastic mechanics model of the casing-cement-combination formation (Equation (4)) mentioned above is used to solve the stress state of the cement ring, and the cement mechanical parameters are substituted into the corresponding strength criteria (Mohr-Coulomb criterion and tensile failure criterion), the failure of cement ring and its failure mode can be determined (Figures 3(a) and 3(b)). If the radial displacement of each boundary calculated according to the boundary displacement model of cement ring assembly (Equations (6)–(9)) satisfies Equation (10) in the trial production or production operation of a certain well, it can determine whether microclearance failure occurs on the first or second cementing surface of cement ring under this operation condition [19–21] (Figure 3(c)).

### 4. Stress-Strain Characteristics of Cement Stone

Compared with the elastomer with the crystal structure of casing steel, cement stone is an atypical elastomer of mixed material and can be regarded as an elastoplastic body. In terms of microstructure, cement stone has certain defects, and its mechanical properties and stress-strain response are affected by various microdefects (microcrack-pore, amorphous mixture) [3, 12, 22]. These structures and formations will make the strength of the cement stone increase with the loading strength and rate of the trial production operation, and the rate of strain increase decreases significantly, eventually developing into large cracks, which basically lose strength through the cement stone [22–25]. The mechanical properties of cement stone are the basic condition to maintain its integrity. The mechanical properties of cement stone made by different cement slurry formulas are significantly different. Therefore, the author needs to test the stress-strain law of cement stone under the operating conditions of horizontal well fracturing and drainage. The strength and elastic parameters of cement stone are the data basis for the subsequent failure analysis of cement ring.

The cement slurry with the same formula for casing cementing in the horizontal well section of Jimsar shale oil well was collected to prepare 6 cement samples with a density of 1.6 g/cm³ (Figure 4). The uniaxial compressive strength and triaxial compression strength testing devices were adopted for the mechanical testing of cement stone, and the stress-strain conditions were observed and recorded (Figure 5). The mechanical parameters obtained are uniaxial compressive strength, Young's modulus, Poisson's ratio, cohesion, internal friction Angle, etc. (Tables 1 and 2).

### 5. Example Analysis

Since 2012, CNPC has made great efforts to innovate geological understanding and tackle key engineering problems in continental shale oil. The Jimsar shale oil has gone through three stages of exploration and discovery, pilot test, and
Table 2: Triaxial stress test results of cementing cement stone in Jimsar shale oil reservoir.

| Serial number | Density (g/cm³) | Confining pressure (MPa) | Modulus of elasticity (GPa) | Peak stress (MPa) | Cohesion (MPa) |
|---------------|----------------|--------------------------|-----------------------------|------------------|----------------|
| C2            | 1.6            | 5                        |                             |                  |                |
|               | 3.0            |                          | 6.00                        | 12.00            |                |
|               | 9.0            |                          | 18.00                       | 24.00            |                |
|               | 12.0           |                          | 30.00                       |                  |                |
| C4            | 1.6            | 8                        |                             |                  |                |
|               | 5.09           |                          |                             |                  |                |
|               | 43.61          |                          | Angle of internal friction  |                  |                |
| C5            | 1.6            | 12                       |                             |                  |                |
|               | 9.96           |                          |                             |                  |                |
development test, and now, it has entered the stage of expanded test, which is a process of “cognizance-practice-recognition-re-practice.” Aiming at drilling speed increase and high-quality reservoir penetration rate, the company has developed supporting technologies such as well structure optimization, excellent and fast drilling, environmental protection and high-performance drilling fluid, and long horizontal section cementing and completion. In order to provide high-quality wellbore conditions for reservoir modification and later production, it is necessary to carry out mechanical integrity evaluation of casing cement ring during fracturing and flowback of horizontal well sealing in combination with typical Jimsar shale oil Wells. At the same time, the influence factors of cement ring integrity are studied, and the sensitivity analysis is mainly carried out for the strength parameters of cement stone, to find the best parameter combination, and to simulate the best technical countermeasures.

5.1. Typical Well Basic Parameters. Well JHW00421 is a typical ultralong horizontal well in Jimsar shale oil. The target formation is the Permian Lucaogou Formation (P 2L 2). The final vertical depth of the target is 2747.1 m. According to the analysis of adjacent well data, the formation pressure of the target formation is about 32.3 MPa, the in situ stress is 60.5 MPa, the average porosity is 8.9%, the average permeability is 35.7 mD, and the formation fracture pressure is about 65.6 MPa. The offset of the wellhead is 174 m, the orientation of the horizontal borehole is 260°, and the well inclination angle is 84~87°. In order to drill the ultralong horizontal section (3,100 m) safely, a three-hole structure was adopted (Figure 6). A Φ444.5 mm bit was used to run the 339.7 mm surface casing to a depth of 500 m. The cement slurry was returned to the surface to seal off loose strata on the surface. In the second opening, Φ311.2 mm drill bit was used to drill to the end of the bottom boundary of Shaofanggou Formation, and 244.5 mm technical casing was run. Cement was returned to about 1500 m to seal the possible oil, gas, and water layers of Wutonggou Formation and its upper unstable strata, creating conditions for safe and fast drilling in the lower horizontal section. In the third opening, Φ215.9 mm drill bit was used to drill to complete the drilling depth, and the casing of 139.7 mm P110 oil layer was run, and the cementing slurry was returned to about 2550 m. The elastic modulus of casing is 206 GPa and the Poisson’s ratio is 0.3. During fracturing, the injection pressure of fluid in the pipe is 70~85 MPa, and the first bonding strength $S_{11}$ equal to the second bonding strength $S_{12}$ of the cement ring, are 2.6 MPa.

5.2. Stress and Failure Analysis of Cement Ring during Fracturing. Figure 7 shows the radial and circumferential stress distribution of cement ring during fracturing of well JHW00421. The radial stress on the cement ring during fracturing is compression force. The absolute value of the radial stress on the side close to the casing is large, and the absolute value of the radial stress on the side close to the borehole wall is small. The radial stress is about 2.1~3.7 MPa, which is far less than the compressive strength of the cement ring. The tangential stress on the side close to casing is large, while the tangential stress on the side close to wellbore wall is small. The tangential stress is no more than 2 MPa, which

| Bound | System | Series | Group | Depth (m) | Lithologic |
|-------|--------|--------|-------|-----------|------------|
| Cenozoic | Paleogene | | | | |
| Cretaceous | | | | | |
| Jurassic | Upper | Qigu | | | |
| | Middle | Toutunhe | | | |
| | Lower | Xishanyao | | | |
| | | Sangonghe | | | |
| | | Badaowan | | | |
| Triassic | Middle | Kamaray | | | |
| | Lower | Shaofanggou | | | |
| | | Jucaiyuan | | | |
| Permian | Upper | Wutonggou | | | |
| | Middle | Lucaogou | | | |
| | | Jinglinggou | | | |

Figure 6: Shaft structure diagram of well JHW00421.
is less than the tensile strength of cement ring (3 MPa). According to the comparative analysis of radial stress, tangential stress, compressive strength, and tensile strength of cement stone, it is concluded that the cement ring will not suffer compression and tensile failure. The Moire stress circle was drawn based on the normal stress and shear stress on the inner and outer surfaces of the cement ring. It was found that the stress circle was located below the Coulomb
stress failure envelope (Figure 8). The analysis results show that the cement ring will not be damaged by compression during the horizontal well fracturing under the condition of qualified cementing quality.

5.3. Failure Analysis of Microclearance of Cement Ring in Backflow Period. According to the theoretical model of cement ring microclearance, the main influencing factors of microclearance are the pressure difference between inside and outside wellbore, Young’s modulus of cement, compressive strength, and Poisson’s ratio, etc. As shown in Figure 9, the simulation analysis concluded that during the flowback period after fracturing, the compressive strength and Poisson’s ratio of the cement stone had little influence on the microclearance of the cement ring. However, when the pressure difference between inside and outside wellbore is 20 MPa, the microclearance of cement ring changes step by step with Young’s modulus. When Young’s modulus is less than 6 GPa, there is no gap in cement ring. When Young’s modulus is greater than 6 GPa, the microclearance of cement ring fails, and the microclearance reaches 30 μm. On the premise that the mechanical properties of cement stone are determined, the microclearance of cement ring is approximately proportional to the pressure difference between inside and outside wellbore.

It is assumed that in the flowback period of fracturing fluid, the microclearance of cement ring is greater than 0.03 mm, which is considered as the cement ring failure. The study believes that the critical pressure difference inside and outside the wellbore when the microclearance failure occurs in the flowback period of fracturing fluid is inversely proportional to Young’s modulus of cement stone (Figure 10). It can be seen from the figure that the elastic modulus of cement stone in this well is about 3.5-4.1 GPa, and the critical pressure difference between the inner and outer wellbore of flowback should be less than 25 MPa.

6. Conclusion

(1) In unconventional oil and gas development, multistage or volumetric fracturing is used in horizontal Wells. During the fracturing process of horizontal wells, fluid pressure in the casing increases and casing expands, which may lead to compression failure or tensile failure of the cement ring. During fracturing fluid flowback, fluid pressure in the casing decreases and casing shrinks, which may lead to microclearance between casing and cement ring. Therefore, the main failure modes of cement ring in horizontal well section are radial compression or...
circumferential tensile failure in the fracturing stage and microclearance failure in the flowback stage.

(2) The development layer of Jimusar shale oil is Lucaogou Formation, and its burial depth is about 2000~5000 m. With the increase of buried depth, the fracture pressure increases continuously but does not exceed 100 MPa. Under the condition of qualified cementing quality, the cement sheath has enough strength, and the cement ring of Jimusar shale oil horizontal well will not fail during fracturing.

(3) According to the theory of cement annulus microclearance, the main factors affecting the failure of cement annulus microclearance in flowback period are the pressure difference between inside and outside wellbore and Young’s modulus of cement stone. The critical pressure difference between inside and outside wellbore is inversely proportional to Young’s modulus of cement when microclearance failure occurs in the fracturing fluid flowback period. Therefore, it is necessary to optimize the formulation of cementing slurry, add a certain proportion of ductile materials to reduce the elastic modulus of cement, and control the wellhead back pressure and flowback fluid quantity appropriately to reduce the pressure difference between inside and outside the wellbore and prevent the failure of cement ring.

Data Availability

No additional data are available.

Conflicts of Interest

The authors declare no conflict of interest.

Authors’ Contributions

Hu Yang performed the experiment and wrote the manuscript. Penggao Zhou contributed to the conception of the study. Shifu Yu contributed significantly to the analysis. Jiancai Li performed the data analysis. Jiwei Wu helped perform the analysis with constructive discussions.

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