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Abstract: During the development of complex gas reservoirs, the risk decision-making problem often emerges. Thus, the study on risk assessment is an important tool used to identify potential hazards and create appropriate avoidance measures accordingly. Based on the analysis of seven types of risk factors in gas reservoir development planning, this paper aims to clarify the logical relationship between the risk factors in the strategic planning of natural gas development. The comprehensive research on target risks in the gas reservoir development planning based on stochastic simulation was carried out. The "probability curve scanning method" was used to evaluate objective risk factors, while the decision-making risk factors were evaluated using the "probability curve displacement method". According to the realization probability and dispersion degree of the planned target combined with the risk grade evaluation matrix, the planning target evaluation risk grade was implemented. Moreover, the planning unit risk grade evaluation was obtained at different stages. Regarding the specific production capacity conditions in gas wells (horizontal and vertical wells) and gas reservoir water invasion – the probability method with Monte Carlo stochastic simulation was used to calculate the production and water invasion volumes. The established decision-making risk technology for gas reservoir development, along with the associated supporting procedures can be used to evaluate the risks of reservoir development planning, production, and water invasion.

Keywords: Gas reservoir; Risk decision-making; Monte Carlo method; Comprehensive evaluation; Productivity risk

1 Introduction

Sichuan Basin is the most promising basin in China in terms of natural gas exploration and development; its total natural gas reserves are approximately 66×10^{12} m^3, ranking first in China. In recent years, the production of natural gas has maintained a continuous growth, with the daily production capacity exceeding $1.05\times10^{8} m^3$. The annual natural gas production accounts for roughly 17.5% of the total national energy output. Furthermore, Sichuan Basin is among the major foundations of the Chinese "West-to-East natural gas transmission project".

When considering Sichuan Basin exploration, the carbonate sequences including the Middle Permian and the southern Weiyuan Sinian, the high and steep structures of the eastern Carboniferous, the Permian system, and the northeastern Triassic system were successively developed after more than 60 years（Hu et al. 2019）. During 2011-2012, the Sinian Dengying Formation and the Cambrian Longwangmiao Formation in central Sichuan Basin were a place of a great breakthrough in natural gas exploration, becoming vital fields for the increase of the conventional natural gas storage and production in the basin（Du et al. 2014; Wei et al. 2015）. In recent years, many scholars have carried out numerous studies to evaluate the development properties of various types of gas reservoirs. Yang et al. (2013) proposed nine types of evaluations to determine the horizontal well development effects. Additionally, a comprehensive evaluation system was established by combining multiple disciplines – technology, management, and economy. By using the life cycle and post-evaluation theory methods, Yao et al. (2019) established the technical and economic evaluation system for the natural gas industry. The input and output of each natural gas industry chain segment were set as priorities. Based on the comprehensive evaluation method philosophy, Zeng et al. (2018) established the system for the evaluation of technical development effects in the development of integrated gas reservoirs; the water in Sichuan Basin was used. By employing the theoretical gas reservoir engineering methods, numerical simulation, and economy evaluation technology, Wang et al. (2011) proposed a reasonable development technology policy suitable for the Puguang gas field. By considering both the dynamic and static characteristics, Cheng et al. (2020) established a reserve evaluation unit partition, reserve classification and evaluation, and reserve succession sequence in gas reservoirs with low permeability and densification. A set of appropriate technical countermeasures for the development of different types of reserves was proposed. Li et al. (2020) studied the main evaluation indices for the development of large carbonate gas reservoirs. The differences between the development effects of typical gas reservoirs and the influencing factors were analyzed, providing the most influential factors affecting the carbonate gas reservoir development. Tan et al. (2020) carried out exploratory research on benchmarking management of natural gas development. A total of 24 natural gas development indicators were selected. It allowed them to establish the first benchmarking index system for natural gas development. According to the gas reservoir characteristics detected in the second Xu jiahe Formation member (the XC block of the western Sichuan depression), Wu et al. (2020) divided the gas wells with industrial productivity into four production modes. Cheng et al. (2020) established a reserve evaluation unit, along with the reserve classification and evaluation, gas reservoir reserve succession sequences of low permeability, and densification. The appropriate technical countermeasures for the development of different types of reserves were proposed. Moreover, Bing et al. (2020) established a method for the classification of the offshore low-permeability gas reservoirs building on and integrating the experience in the offshore low-permeability gas reservoir classification. Li et al. (2019) established a comprehensive classification standard for the reservoirs, which was based mainly on reserve abundance. The proposed standard was combined with the results of both the dynamic and static classifications. As a result, the reserves in the study area were divided into four groups. The research results provided certain guidance for sustainable and stable production during the middle and late periods of development in Sulige.

During the development of complex gas reservoirs, it is often necessary to overcome the overcome decision-making risk, such as prediction of the well development effectiveness before drilling. Additionally, wastewater harnessing for active water-drive gas reservoirs and the development program preparation before the confirmation of reserves. Through the accumulation of long-term practical experience, some understanding was gained on the probability that some adverse factors could occur, along with the associated degree of hazard. In the past, deterministic analysis was used as the basis to provide technical support for the decision-making process, meaning that managing the above-mentioned uncertain factors was difficult. Therefore, it is necessary to carry out the research study on risk evaluation considering the influences of multiple factors. The research on risk evaluation is vital in identifying potential threats and formulating effective avoidance measures. Due to the long-term nature of gas reservoir development and the uncertainty of future changes, it is necessary to carry out a systematic risk analysis to improve its significance to industrial practice. By effectively identifying the critical gas reservoir development risks and suggesting the appropriate preventive measures for different environments, threats and potential risks can be minimized.

2 Mathematical Model and Risk Decision-making Method in Gas Reservoir Development

2.1 Planning risk factors in gas reservoir development

(1) Resource scale risks

The resource risks account for the following three factors: the resource quantity, the proven reserves that the resource quantity can be converted into, and the disposable proven reserves.

The resource quantity is changing with the increase in resource exploration investment, the improvement of theoretical understanding, and the advances in methods and technologies. The resource quantity can be converted into proven reserves, but the success rate is influenced by geological knowledge, available technology, and investment, while the conversion rate remains rather uncertain. Moreover, even the scale of proven reserves is risky to assess; the industry standard specifies that for proven reserves the error range within 20% is acceptable, as shown in Table 1.

Table 1 Acceptable error ranges for various reserve grades

Category of reserves	Acceptable error ranges of reserves
Controlled reserves	±50%
Basic proven reserves	±30%
Proven reserves	±20%

(2) Geological development risks

Geological development risks include the objective risks that affect the difficulty to develop natural gas resources. Since the resources are buried underground, it is impossible to obtain direct insight; however, the insight can be built indirectly by observing earthquakes, drilling, well logging, and well testing. Due to the limited geological data, interpretation results are uncertain, which primarily includes the understanding of structural gas reservoir characteristics, the reservoir continuity and heterogeneity, degree of its development fracture, and the activity degree of the edge-bottom water.

(3) Planning and deployment risks

The risks of planning and deployment mainly consider whether the development pace, workload, and investment meet the actual production demand. The risks of the poor geographical environment, changes in drilling cost, and construction team quality directly affect the construction progress, production capacity, and other planning and deployment activities.

(4) Technology level risks

The technology level risks mainly refer to the effectiveness of development means used in various gas reservoir types. As technological advances and development are slow processes, the potential for technological progress can be either overestimated or underestimated during strategic planning.

(5) Economic benefit risks

Influenced by the uncertainty of natural gas economy evaluation parameters, such as sale prices, operating costs, and construction investments, during the planning, risks of whether the planned benefit target can be achieved emerge.

(6) Pipeline market risks

The integration of upstream, middle, and downstream nodes in the supply chain is among the most remarkable features within the natural gas industry. The field production, along with the transmission pipeline network, and finally, gas storage to users, is a huge system; as such, its elements are interrelated. Thus, the strategic planning of natural gas development should also consider the coordination of upstream, middle, and downstream nodes within the supply chain, along with their sustainable development. Finally, middle and downstream constraints can limit the natural gas production scale, increasing the uncertainty of planning objectives.

(7) Macroscopic policy risks

The original policy intention is to ensure the efficient scientific development of resources, as well as their safe and stable supply. The underlying premise is to ensure health, safety, and environmental protection. However, some fiscal and tax policies related to natural gas make its development harder, bringing uncertainty.

To sum up, the mechanisms of seven risk factor types, along with their modes and effects on the planning targets, are also different. Resource scale and development geology risks are objective risks, which can only be detected – it is not possible to mitigate them. Therefore, regarding objective risks, it is necessary to improve the understanding of objective laws and increase the evaluation accuracy, aiming to make it closer to the real situation. Doing so will help to reduce the uncertainty in strategic planning to a minimum level. Moreover, planning and deployment risks, economic benefit risks, pipeline market risks, macroscopic policy risks, and technology level risks belong to the decision-making risks. The decision-making risks are controlled by an individual's subjective initiative and can be both understood and mitigated.

2.2 Comprehensive risk evaluation of gas reservoir development planning target based on the stochastic simulation

2.2.1 Stochastic simulation of development indicators

(1) Simulation principle of planned production

The production risk evaluation in strategic planning of natural gas development is a production optimization process that considers multiple risk factors. The action mechanisms of seven risk types on the planned production vary. The evaluation model is essential to determine the logical relationship between production and the risk factors. Through analysis, the planned production risk simulation process is divided into two stages. Firstly, the two types of objective risks, resource scale, and development geology are considered to obtain the maximum production potential. Secondly, the remaining decision-making risks are considered, and the maximum production potential is restricted step-by-step, aiming to obtain the production that will satisfy the constraints. Those two stages are referred to as the unconstrained production simulation stage and constrained production simulation stage, respectively.

(2) Unconstrained production simulation

The unconstrained production simulation only considers the natural gas resource scale and development geology risks. The production level obtained from simulation can be regarded as the maximum natural gas development potential. Furthermore, the production composition method is employed for calculation; the evaluation unit is divided into three groups. The first group includes the parts that are proven and developed, the second group parts are proven but not developed, while the third group includes parts that are yet to be proven. Each part is calculated separately at first, followed by the summing up all three to obtain the gas area production:

$$Q_t = \sum_{i=1}^{m+n+l} q_{i,t} = \sum_{i=1}^{m} PD_{i,t} + \sum_{i=m+1}^{m+n} PUD_{i,t} + \sum_{i=m+n+1}^{m+n+l} UD_{i,t} \tag{1}$$

The basic evaluation unit in the production composition method is a single gas field (or a cluster of gas fields that can be combined). Generally, a gas field development goes through several stages, including the production start, stable production, decline, and abandonment. The production at different stages is calculated as (2):

$$q_{i,t} = \begin{cases} \dfrac{t-1}{C_T \times \overline{q_i}}, t < C_T \\ \overline{q_i}, C_T < t < PL + C_T \\ q_{i,t-1} \times R_d, PL + C_T < t < T_f \\ 0, T_f < t \end{cases} \tag{2}$$

(3) Constrained production simulation

The constrained production simulation has to consider various decision-making risks faced by natural gas development; therefore, it is necessary to adjust the production of gas fields and gas zones. To start, it should be considered whether the investment in the gas field is made, if the workload is sufficient, does the surface supporting capacity meets the production demand, and if the development technology is effective, among others. Once all the factors are considered, the gas field production is adjusted accordingly:

$$q'_{i,t} = \min(q_{i,t}, q_{i,\mathrm{m}}) \tag{3}$$

Which, $q_{i,\mathrm{m}}$ —constrained production.

Secondly, after considering the constraints like area gas market demand, pipeline transmission capacity, and macroscopic policy, the gas field production, and the gas area are adjusted. When the sum of gas field production is less than or equal to the constrained gas area production, the production of either the gas area or gas field does not need to be adjusted. However, when the total production of gas fields is greater than the constrained gas area production, some gas fields are to be adjusted. The basic adjustment principles include: adjustment should be prioritized to unprofitable or less profitable gas fields, to gas fields that are easy to recover production, and to gas fields where the production system has a limited impact on the ultimate recovery ratio. Additionally, minimum production requirements ensuring the normal operation of surface gathering and transportation plants should be satisfied. After the constraints are considered, functions simulating the gas field production are represented by expressions (4) and (5), as follows:

$$\sum_{i=1}^{x+y} q'_{i,t} = \begin{cases} \sum_{i=1}^{x+y} q'_{i,t}, \sum_{i=1}^{x+y} q'_{i,t} < Q_t \\ \sum_{i=1}^{x} q'_{i,t} + \frac{\sum_{i=x+1}^{x+y} q'_{i,t}}{\chi_{i,t}}, \sum_{i=1}^{x+y} q'_{i,t} > Q_t \end{cases} \tag{4}$$

$$q''_{i,t} = \begin{cases} q'_{i,t}, i < x \\ \frac{q'_{i,t}}{\chi_{i,t}}, x < i \end{cases} \tag{5}$$

Q_t ——Constrained upper limit production.

By adjusting gas field production twice and gas area production once, it is possible to complete a yearly simulation of gas field and gas area production. By calculating the recovery degree of all the gas fields at the end of the year, their development stages can be determined. The function is selected to assess the gas field production of the following year according to Formula (3), satisfying the constraint of both the previous and following gas field time nodes.

(4) Probabilistic simulation of planned production

There are many uncertainties when calculating the natural gas production parameters. Theoretically, any combination of parameters can occur. Thus, aiming to simulate all the possible production scenarios, the Monte Carlo stochastic simulation method was introduced. Firstly, the probability curves of the quantified risk indicators were determined according to the risk factor characteristics. Furthermore, the Monte Carlo method was used to randomly interpolate the quantified risk indicators to calculate the production during the planning period. Finally, the production probability simulation during the planning period was achieved through multiple stochastic calculations.

2.2.2 Comprehensive risk evaluation of development planning risk indicators

(1) Configuration of risk evaluation indicators

The core of risk evaluation is to assess whether the planning objectives can be achieved. The probability of achieving the planning target is generally represented by the cumulative probability; the production of stochastic simulation is often greater than the planning target. Moreover, the higher the probability and greater the planning target, the higher the realization probability. However, in the actual implementation process, there will also be a high planning target realization probability in combination with the poor implementation effect, mainly due to the large dispersion of probabilistic production. For this reason, two indicators, “realization probability” and “dispersion degree”, were introduced to assess the risk degree. The former refers to the arithmetic mean of the absolute value of the difference between the stochastic simulation value and the expected value, further divided by the expected value.

(2) Risk grade evaluation matrix

By carefully considering the planning target realization probability and the probabilistic production dispersion degree, a risk grade evaluation matrix is established. The risks are categorized into four levels, as shown in Figure 1.

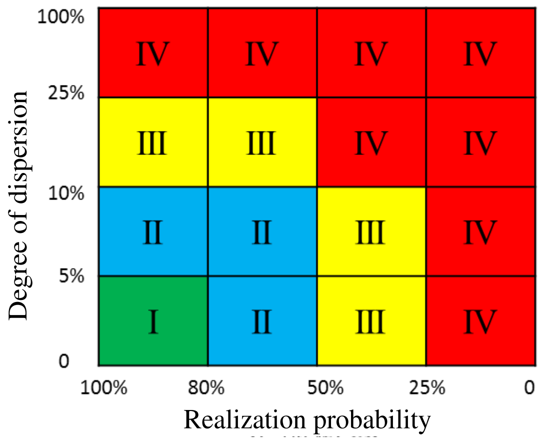

Fig. 1 Risk matrix

Risk level I combines a high planning target realization probability (≥ 80%) and a low dispersion degree (≤ 5%). Thus, the planning target risk is low.

Risk level II considers a relatively high planning target realization probability (50% to 80%) with a relatively low dispersion degree (≤ 10%), or a high planning target realization probability (≥ 80%) and a relatively low dispersion degree (5% to 10%). Therefore, the planning target risk is acceptable.

Risk level III combines a low planning target realization probability (20% to 50%) and a relatively low dispersion degree (≤ 10%), or a relatively high planning target realization probability (≥ 50%) and a relatively high dispersion degree (10% to 25%). Thus, the planning target risk is high, indicating the need for further optimization.

Risk level I includes risks with a very low planning target realization probability (≤ 20%) and a high dispersion degree (≥ 25%), or a low planning target realization probability (20% to 50%) and a relatively high dispersion degree (10% to 25%). Therefore, the planning target risk is high, which is unacceptable.

(3) Risk sensitivity evaluation

Similarly, strategies needed to reduce the risk grade can be classified into two groups: improving the realization probability and reducing the dispersion degree. Combined with the characteristics of seven risk factors, corresponding sensitivity evaluation methods are established for various risk types.

The method used to evaluate objective risk factors is known as the "probability curve scanning method". Since the objective risks can only be detected, but cannot be changed, the production can only be calculated using various probabilities according to the cumulative probability curve distribution laws of the quantified objective risk indicators. They can be used to evaluate the objective risk points and clarify which risk points are the most prominent. By expanding the research on objective risks, improving the awareness of risk factor degrees, and reducing the planning target dispersion degree, risks can be reduced.

Decision-making risk factors are evaluated using the "probability curve displacement method". Since the decision-making risks can be both recognized and mitigated, the probability curve of quantified decision-making risk indicators can be altered. According to the cumulative probability curve of decision-making risk factors, the magnitude of changes in the decision-making risk on production is assessed. This method can be used to evaluate the sensitivity of decision-making risk points to planning targets, improve the probability of achieving the planning targets through individual's subjective initiative, and effectively control the strategic planning risks.

2.3 Risk assessment of gas reservoir production based on the comprehensive fuzzy evaluation

2.3.1 Evaluation unit division

The units that are to be evaluated are divided into three groups:

A – Proven and developed; B – Proven but not developed; C – Reserve areas to be proven

2.3.2 Data preparation

Similarly, the data that has to be prepared can also be divided into three types.

(1) Exploration, prior development, and current data;

(2) Planning program targets and deployment;

(3) Risk factor probability curves.

Among them, prior and current data are premises for the risk research, whole planning targets and deployment are the risk research object. Finally, risk factor probability curves are critical to quantitative risk evaluation.

2.3.3 Risk grade categorization

According to the risk indicator system and previously obtained production model, stochastic simulation was carried out multiple times (in this paper, it was run 1000 times). The simulation results were sorted in descending order. The production corresponding to the 100th is known as P10 production.

Similarly, those corresponding to the 500th and the 900th simulation were denoted as P50 and P90 production, respectively. All the productions enabled the authors to obtain the probability trend chart. According to realization probability and planning target dispersion degree, together with the risk grade evaluation matrix (Figure 1), risk grade evaluation can be carried out for the planning target. Finally, the resulting evaluations of planning unit risk grades at various stages are shown in Table 2.

Table 2 Risk grade table for gas reservoir development planning unit

Evaluation unit	Year 2015	Year 2020	Year 2025	Year 2030
A	I	I	III	IV
B	-	II	II	III
C	-	I	III	IV

2.3.4 Evaluation of main risk points and analysis of avoidance measures

(1) Evaluation of main risk points

According to the risk grade table, the main risk points were analyzed according to the production target of the reserve area that is to be proven in 2025. The sensitivity evaluation results of objective risk factors were discussed to evaluate the relationship between the objective risk factors and gas field reserves. Additionally, the sensitivity evaluation results of decision-making risks were discussed to determine the relationship between the decision-making risks and the factors including investment scale and technology level.

(2) Analysis of avoidance measures

According to the above-presented evaluation results of the main risk points, it was suggested that appropriate risk avoidance measures are carried out. For instance, further boost the investments in exploration, and mitigate key problems through science and technology. By doing so, it is possible to increase the scale of new reserves and improve the utilization of both the reserves and production.

3 A Case Study on Risk Decision-making

The Longwangmiao Formation gas reservoir in Moxi was used as an example. The Monte Carlo method was applied to generate 1000 parameter combinations, in which the gas-bearing area A mean value and the variance were 805 and 100, respectively. Furthermore, the mean value and the variances are as follows: for the average effective thickness h they are 35 and 15, respectively, for the average effective porosity they are 8.4 and 1.8, respectively, for the average original gas saturation Sgi they are 52.535 and

14.5, respectively. Finally, the original gaseous Z-factor Zi is 1.43273, the average original gas reservoir pressure Pi is 76.02, and the gas reservoir temperature T is 415.26.

3.1 Production risk evaluation

The gas well production is a production capacity parameter that reflects the current production capacity of oil and gas well. As such, it is mainly affected by the geological conditions within the reservoir. Considering the specific situation of the gas well production capacity (horizontal and vertical wells), this paper applies the Monte Carlo stochastic simulation to calculate the production. The production of the horizontal well can be found using Formula (6):

$$q_{sc} = \frac{\pi k h T_{sc}\left(P_i^2 - {P_{wf}}^2\right)}{2\mu T P_{sc}[\ln \frac{a+\sqrt{a^2-\left(L/2\right)^2}}{L/2} + \frac{h}{L}\left(\ln \frac{r_{eh}}{r_{wh}} + S\right)]} \tag{6}$$

where $a = 0.5L[0.5+\sqrt{0.25+2\left(r_{eh}/4\right)^4}]^{0.5}$

where K is permeability (mD); h is gas reservoir thickness (m); P_i is original gas reservoir pressure (MPa); P_{wf} is flowing bottom hole pressure (MPa); μ is viscosity (MPa·s); Z is natural gas Z-factor; T is gas reservoir temperature (K); L is horizontal section length (m); S is skin factor; r_{eh} is a hydrodynamic radius (m); r_{wh} is wellbore radius (m); T_{sc} is ground surface temperature (K); and P_{sc} is standard atmospheric pressure (MPa).

The vertical well production can be as found as (7):

$$q_{sc} = \frac{774.6Kh\left(\psi_e - \psi_{wf}\right)}{T\ln\left(r_{eh}/r_{wh}\right)} \tag{7}$$

where $\psi_e - \psi_{wf} = 2\int_{p_{wf}}^{p_e} \frac{p}{\mu Z}dp$

where q_{sc} represents the oil (gas) well production (m^3/d); K is the reservoir permeability (mD); r_{eh} and r_{wh} represent drainage radius and oil (gas) well radius (m), respectively; h represents the gas reservoir thickness (m); p_e and p_{wf} represent the supply boundary pressure and oil well flowing bottomhole pressure (MPa), respectively; Bo is the crude oil volume factor; μ is the viscosity of crude oil ($mPa{\cdot}s$); T is reservoir temperature (K); ψ_e is the pseudopressure corresponding to the supply boundary pressure; and ψ_{wf} is the pseudopressure corresponding to the flowing bottomhole pressure.

3.2 Water invasion risk evaluation

With the continuous depletion and development of edge-bottom water gas reservoirs, the gas reservoir pressure continuously declines. As a result, edge-bottom water invades into the gas reservoir, breaking through gas wells to various degrees. The production characteristics of gas wells after water breakthrough are very different from their oil well counterparts. Due to the water blocking effect at the bottom of a gas well, the gas well production capacity will be greatly reduced following a water breakthrough. Simultaneously, with the decline of gas well production and the increase of water production, it is easy to form bottom hole fluid. It will, in turn, result in gas well production suspension, seriously affecting its development effect. Additionally, the difficulty of gas reservoir development will be increased, while its recovery ratio will diminish. In this paper, the Monte Carlo stochastic simulation was used to calculate the amount of water influx for the specific water invasion situation (in gas reservoirs). The expression (8) shows the water influx amount:

$$W_e = W_p B_w + \omega G B_{gi} \tag{8}$$

$$\omega = 1 - \frac{P_p}{P_{pi}(1 - G_p / G)} \tag{9}$$

where B_{gi} is gas volume factor under the original gas reservoir pressure; B_w is formation water volume factor; G_p is cumulative gas reservoir gas production ($10^8 m^3$); G represents the reservoir gas reserves ($10^8 m^3$); P and P_i are the gas reservoir pressure and the original gas reservoir pressure (MPa), respectively; P_p and P_{pi} are the gas reservoir pseudopressure and the original gas reservoir pseudopressure, respectively; W_e represents the water influx amount ($10^4 \mathrm{m}^3$); W_p is water production amount ($10^4 \mathrm{m}^3$); Z is gaseous Z-factor; and w is the water invasion volume factor.

Regarding production period and recovery degree, a suitable reduction in production allocation can extend the stable production life significantly – from 8.8 years to 10.3 years. Additionally, it can increase its recovery ratio to 68.4% at the end of the 30-year period. The forecast data comparison of various development indicators is shown in Figure 3. Therefore, the production reduction can be used as an alternative to the water control scheme.

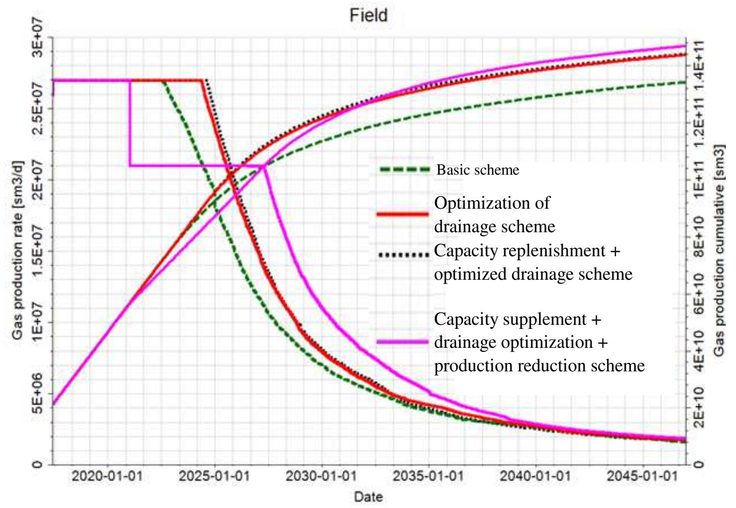

Fig. 3 Comparison of production curves for various production ways

3.3 Indicators of recommended program

The recommended program IV, production supplementary, and drainage optimization can maintain a production scale at nine billion cubic meters. During a follow-up, six development wells were included, each having a production allocation of $30\times10^4m^3/d$ (on average). Meanwhile, the production allocation of old wells was reduced. Moxi X210 well started the active drainage of 400 m^3/d in July 2018. Only after wellbore liquid was found in Moxi 009-3 well group, 009-3 well group replaced Moxi X210 well. The active drainage through manual drainage measures was used. Furthermore, Moxi 009-3-X2 and 009-3-X3 wells drained away 200 m^3/d and 200 m^3/d of water, respectively. Moreover, the 009-8-X1 well had encountered difficulty in bringing water; therefore, manual drainage measures were adopted and drainage of 400 m^3/d was reached.

The production of gas wells located in the south wing of the Moxi 8 well area was reduced to $130\times10^4m^3/d$. In the early stages, the Moxi 008-X23 and the 008-H26, located in the north wing of the Moxi 8 well area, were allocated with productions of $40\times10^4m^3/d$ and $30\times10^4m^3/d$, respectively. In the future, when bringing the water becomes more difficult, manual drainage measures will be adopted, most likely in August 2025, and March 2022. The drainage is planned to reach 300 m^3/d.

The stable production of the gas reservoir is planned to last for 8.8 years, resulting in the total production of natural gas equal to $880.44\times10^8m^3$ by the end of the stable production phase. Moreover, the production of $1452.75\times10^8m^3$ is expected by the end of an estimated 30-year period. The gas reservoir recovery degree is 65.70%. In the 10-year evaluation period, the maximum annual water treatment capacity will be $82.66\times10^4m^3/a$, with the maximum daily water treatment capacity of $2505m^3/d$. The accumulative gas reservoir water production in 10 years will be $357.99\times10^4m^3$, while the accumulative drainage will be

$306.90\times10^4 m^3$.

4 Conclusions

During the development of complex gas reservoirs, the risk decision-making problem often emerges. Thus, the study on risk assessment is an important tool used to identify potential hazards and create appropriate avoidance measures accordingly. Based on the analysis of seven types of risk factors in gas reservoir development planning, this paper aims to clarify the logical relationship between the risk factors in the strategic planning of natural gas development, the conclusions are drawn that:

(1) The comprehensive research on target risks in the gas reservoir development planning based on stochastic simulation was carried out. The "probability curve scanning method" was used to evaluate objective risk factors, while the decision-making risk factors were evaluated using the "probability curve displacement method".

(2) According to the realization probability and dispersion degree of the planned target combined with the risk grade evaluation matrix, the planning target evaluation risk grade was implemented. Moreover, the planning unit risk grade evaluation was obtained at different stages.

(3) Regarding the specific production capacity conditions in gas wells (horizontal and vertical wells) and gas reservoir water invasion – the probability method with Monte Carlo stochastic simulation was used to calculate the production and water invasion volumes.

(4) The established decision-making risk technology for gas reservoir development, along with the associated supporting procedures can be used to evaluate the risks of reservoir development planning, production, and water invasion.

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Figures

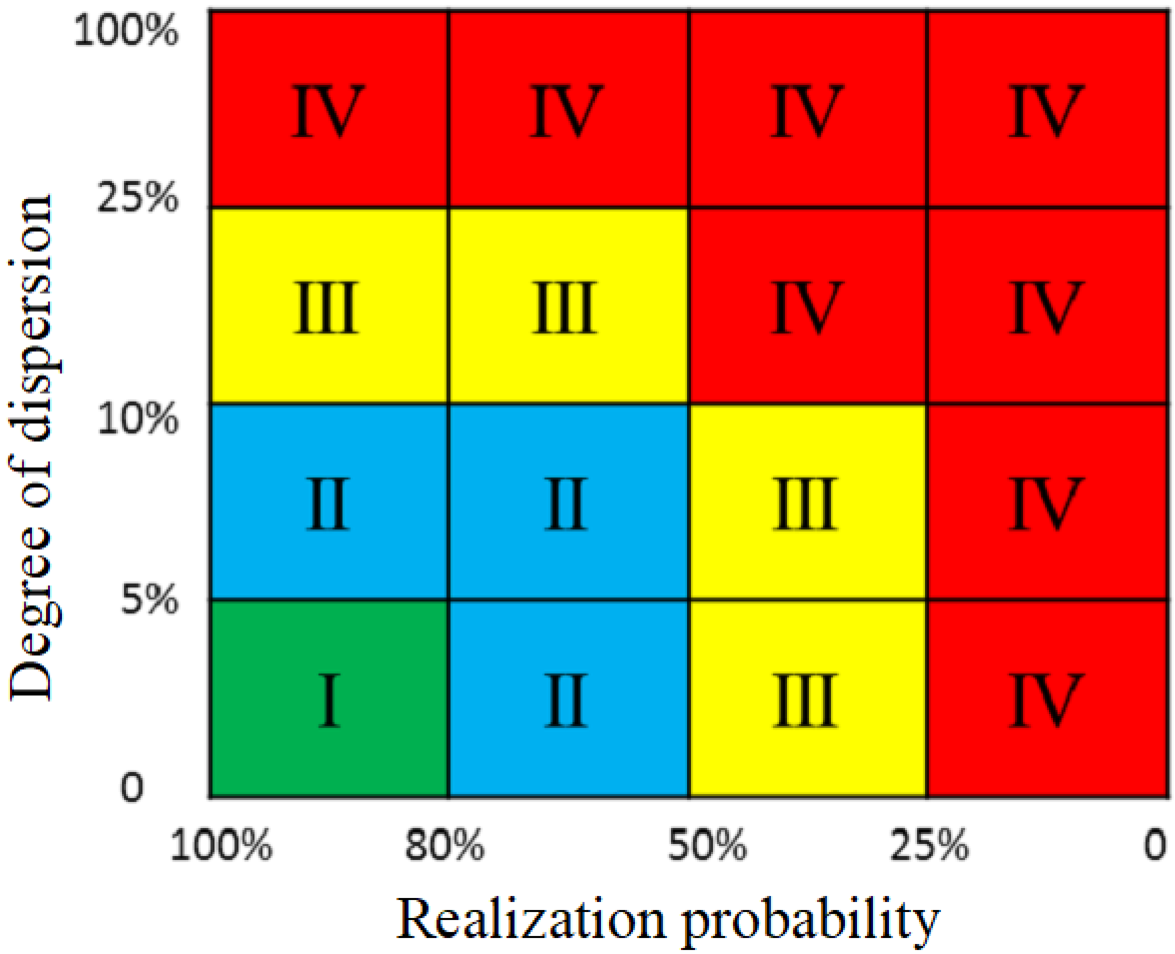

Figure 1

Risk matrix

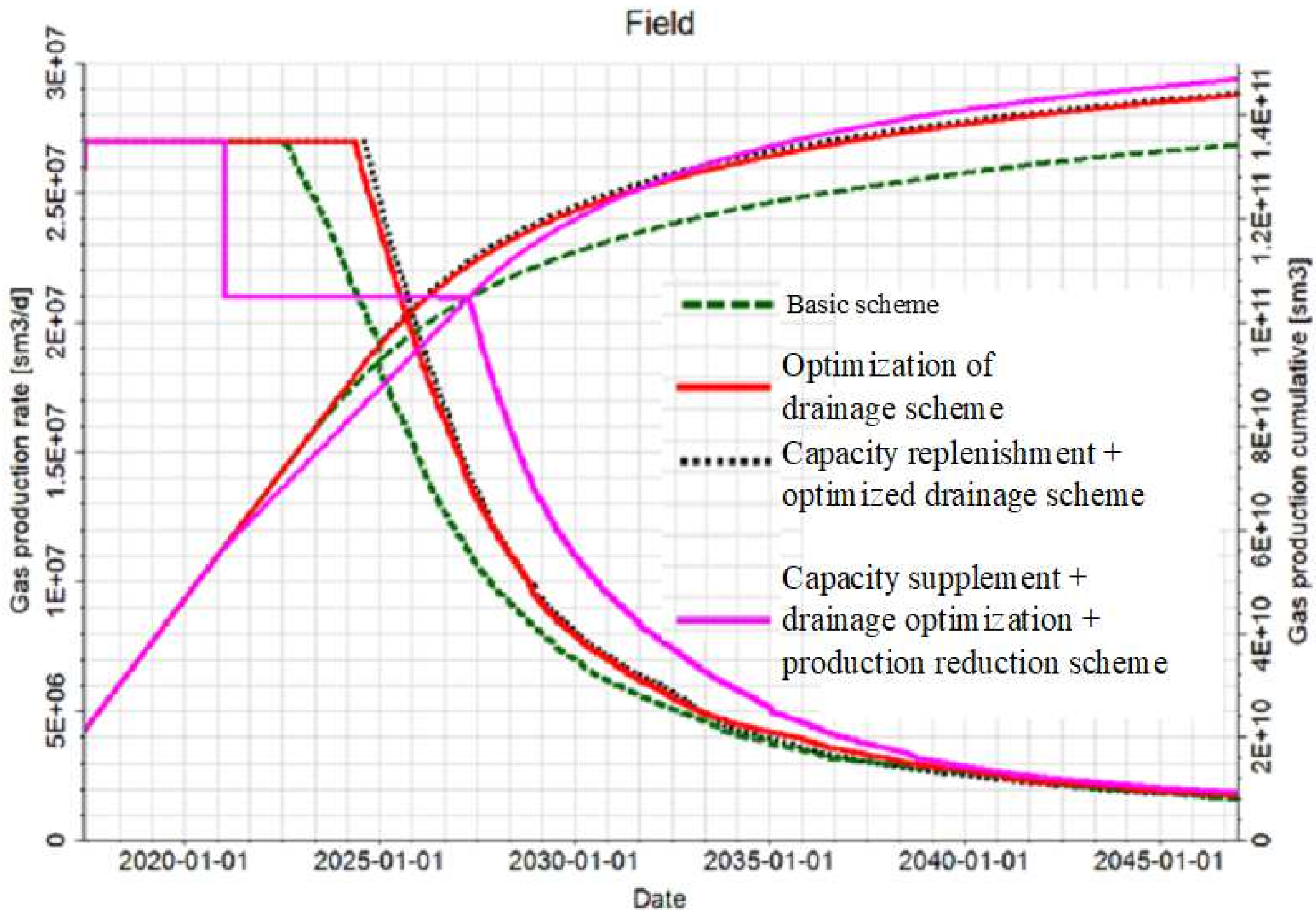

Figure 2

Comparison of production curves for various production ways