Quantitative risk assessment of wellbore collapse for volcanic rock formation in Sichuan Basin

Qiang Su¹, Jianhua Guo¹, Tianshou Ma²*, Xihui Hu¹

¹ Engineering Technology Research Institute, PetroChina Southwest Oil & Gas Field Company, Chengdu, Sichuan 610052, China
² State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

Corresponding author: matianshou@swpu.edu.cn ORCID:0000-0002-8754-9156

Abstract. Drilling and completion practices for Permian volcanic formation in Sichuan Basin show that the volcanic formation is usually featured by complex lithology, strong heterogeneity, and strong uncertainty. Consequently, a huge risk of borehole collapse is observed during drilling and completion, which seriously affects the safety, efficiency, and costs of natural gas wells. However, the classical analysis method of wellbore stability cannot effectively evaluate the wellbore stability of Permian volcanic formation. Therefore, in view of the complex lithology and strong heterogeneity of volcanic formation, the reliability theory is introduced to conduct the quantitative risk assessment of wellbore collapse for volcanic rock formation. First, the uncertainty analysis model for borehole collapse was introduced based on the reliability theory. Second, the 1D mechanical earth model (MEM) of Permian volcanic formation was proposed by using logging interpretation. Third, the uncertainty of the MEM was assessed by fitting the logging interpretation results. Then, the Monte–Carlo method was used to quantitatively assess the collapse risk of Permian volcanic formation, and the finding was compared with the field testing result. Finally, the sensitivity parameter of borehole collapse was analyzed for Permian volcanic formation. The results indicated that the cohesive strength, internal friction angle, and maximum horizontal stress conformed to a loglogistic distribution; the minimum horizontal stress conformed to an InvGauss distribution, whereas the pore pressure conformed to a Weibull distribution. The equivalent mud weight of critical collapse pressure was approximately 1.88 g/cm³ when the collapse risk was 5% (i.e., reliability: 95%), which is consistent with the actual situation of the YT-1 well. The sensitivity ranking of wellbore stability parameters were as follows: maximum horizontal in-situ stress > pore pressure > internal friction angle > cohesive strength > minimum horizontal in-situ stress. The present method and results can provide theoretical guidance for the prevention and treatment of wellbore collapse incidents in Permian volcanic formation.
1. Introduction

The “Emei” geostrophic movement led to large-scale volcanic eruptions in Sichuan Basin, China; consequently, the volcanic rocks are widely distributed in Sichuan Basin [1-2]. Recently, a wildcat well YT-1 was drilled successfully; a high-yield gas flow of $22.5 \times 10^4$ m$^3$/day was achieved in the YT-1 well, and an extrusive facies volcaniclastic gas reservoir was first discovered in Sichuan Basin, which is a major breakthrough in the exploration of volcanic rock gas reservoirs [3-4]. Permian volcanic rocks, which are widely distributed in Sichuan Basin, which has favorable reservoir conditions for natural gas development and broad prospects for exploration, have become a new exploration field. However, drilling and completion practices for Permian volcanic formation in Sichuan Basin show that volcanic formation is usually featured by complex lithology, strong heterogeneity, and strong uncertainty; thus, a huge risk of borehole collapse occurs during drilling and completion [3], which seriously affects the safety, efficiency, and costs of natural gas wells.

To overcome the wellbore collapse problem encountered during drilling and completing, several scholars had conducted a large number of theoretical studies on wellbore stability, and most of these researches focused on the stress distribution model and failure criterion [5-28]. Regarding the stress distribution models of wellbore stability analysis, including linear elastic, elastic–plastic, poro-elastic, thermo-poro-elastic, chemo-poro-elastic, chemo-thermo-poro-elastic models, and so on [3-19], the poro-elastic model is still the most common used model due to the simple input parameters and higher prediction accuracy. Regarding the failure criterion of wellbore stability analysis, the common criteria are mainly the Mohr–Coulomb, Drucker–Prager, Mogi–Coulomb, modified Lade, Wiebols–Cook criteria, and so on [20-23], the Mohr–Coulomb criterion is still the most commonly used. However, these analysis methods are used for the certain situation of formation properties, and they are unsuitable for wellbore stability analysis of volcanic formation due to the complex lithology, strong heterogeneity, and strong uncertainty. To investigate the influence of uncertainty, Morita [24] conducted an uncertainty analysis of wellbore stability analysis by using a statistical error analysis method. Ottesen et al. [25] conducted a wellbore stability assessment using quantitative risk analysis (QRA). Moos et al. [26] also conducted a comprehensive wellbore stability analysis utilizing the QRA. Al-Ajmi and Al-Harthi [27] conducted the wellbore collapse analysis by utilizing a probabilistic approach and Monte–Carlo simulation. Udegbunam et al. [28] conducted an uncertainty evaluation of wellbore stability prediction. Gholami et al. [29] also utilized the QRA to assess the wellbore stability, and the mud weight window for different failure criteria was determined. Ma et al. [30] analyzed the uncertainty evaluation of safe mud weight window utilizing the reliability assessment method. Chen et al. [31] conducted the risk assessment of wellbore instability based on the reliability theory.

The QRA had been applied successfully to the uncertainty evaluation of wellbore stability, and it can be utilized to analyze the risk of wellbore instability under the condition of uncertain parameters. However, studies on the uncertainty evaluation of wellbore stability for volcanic formation are limited. Therefore, considering the complex lithology, strong heterogeneity, and strong uncertainty of Permian volcanic formation, the reliability theory was introduced to conduct the QRA of wellbore collapse for Permian volcanic rock formation in Sichuan Basin. The present paper is organized as follows: In Section 2, an uncertainty analysis model for borehole collapse is introduced based on the reliability theory. In Section 3, the 1D mechanical earth model (MEM) is proposed by using logging interpretation. In Section 4, the uncertainty of MEM is assessed by fitting logging interpretation results. The Monte–Carlo method was used to assess the collapse risk, the result was compared with the field testing finding, and the parameter sensitivity of borehole collapse was analyzed. The present paper can
provide theoretical guidance for the prevention and treatment of wellbore collapse incidents for Permian volcanic formation.

2. Uncertainty Assessment Modeling of Wellbore Collapse

2.1. Collapse pressure model

For a vertical well, the hoop and axial stresses are the functions of the angle $\theta$, and both hoop and axial stresses reach the greatest value when the angle $\theta = 90^\circ$ or $\theta = 270^\circ$, whereas both hoop and axial stresses reach the lowest value when the angle $\theta = 0^\circ$ or $\theta = 180^\circ$. Thus, when the angle $\theta = 90^\circ$ or $\theta = 270^\circ$, the major and minor effective stresses at the wall of borehole can be obtained, respectively. In addition, given the effect of non-linear effect of elastic modulus, the elastic modulus generally increases with confining pressure. If the linear elastic model is used to calculate the stress at the wall of the borehole, the stress is usually extremely high. Thus, the non-linear correction coefficient is introduced to correct the major stress at the wall of the borehole. Once the corrected major and minor effective stresses at the wall of borehole was obtained, they can be substituted into the Mohr–Coulomb criterion, and the equivalent mud weight of collapse pressure (EMWCP) can be obtained [7, 31],

$$\rho_c = \frac{\eta(3\sigma_{ht} - \sigma_h) - 2CK + \alpha p_p(K^2 - 1)}{(\eta + K^2)\cdot H}\times100$$  \hspace{1cm} (1)

where $K$ is given as follows:

$$K = \cot\left(45^\circ - \frac{\phi}{2}\right)$$  \hspace{1cm} (2)

where $\sigma_{ht}$ is the maximum horizontal in-situ stress; $\sigma_h$ is the minimum horizontal in-situ stress; $\alpha$ is Biot’s coefficient; $p_p$ is pore pressure; $\eta$ is the non-linear correction coefficient (in general, $\eta = 0.95$); $C$ is the cohesive strength; $\phi$ is the internal friction angle; $K$ is a rock material constant related to cohesive strength and internal friction angle; $\rho_c$ is the EMWCP; $H$ is the vertical depth.

2.2. Uncertainty assessment model

According to the reliability assessment theory [32], the influencing factors can be sorted into two groups: loads $Q$ and resistances $R$. For wellbore collapse, load group $Q$ is related to the in-situ stress, pore pressure, and rock properties; the resistance $R$ is related to wellbore pressure and rock strength. Thus, the loads $Q$ and resistances $R$ can be expressed as follows [30]:

$$\begin{align*}
Q &= Q(\sigma_{ht}, \sigma_h, p_p, C, \phi) = \rho_c \\
R &= R(\rho_m) = \rho_m
\end{align*}$$  \hspace{1cm} (3)

where $Q$ is the load, $R$ is the resistance, and $\rho_m$ is the mud weight.

Thus, the function of reliability assessment can be expressed as follows:

$$Z = g(Q, R) = Q - R = \rho_m - \rho_c = \frac{\eta(3\sigma_{ht} - \sigma_h) - 2CK + \alpha p_p(K^2 - 1)}{(\eta + K^2)\cdot H}\times100$$  \hspace{1cm} (4)

where $Z$ is the function of reliability assessment.
Based on the function of reliability assessment, the failure risk of wellbore collapse can be determined. When the function of reliability assessment equals to 0, the wellbore meets the state of limit equilibrium; when the function of reliability assessment is greater than 0, the wellbore can keep stable; when the function of reliability assessment is less than 0, the wellbore will collapse. The reliability of wellbore stability can be expressed as by the following equation [32]:

\[ \beta = \frac{\mu(Z)}{\sigma(Z)} \]  

(5)

where \( \mu(x) \) is the mean of a random variable \( x \); \( \sigma(x) \) is the standard deviation of a random variable \( x \); \( \beta \) is the reliability.

Thus, the reliability probability can be expressed as follows [32]:

\[ P_r = P(Z \geq 0) = P\left((\rho_m - \rho_c) \geq 0\right) = \Phi(\beta) \]  

(6)

where \( P_r \) is the reliability probability of wellbore stability.

The Monte–Carlo simulation was used to solve this model, and the main process of simulation can be described as follows: (1) distribution fitting of random variables and selection of the proper probability distribution model; (2) generation of the random number that meets the distribution function of random variables using the Monte–Carlo method; (3) substitution of the random number into the uncertainty assessment model to calculate the reliability; (4) substitution of the reliability into the reliability probability equation to calculate the reliability probability and to determine the density curve and cumulative curve of reliability probability for wellbore collapse.

3. 1D MEM of Permian Volcanic Formation

The MEM usually covers the rock mechanical properties, pore pressure, and in-situ stresses. For wellbore stability analysis, the rock mechanical properties (cohesive strength and internal friction angle), pore pressure, and in-situ stresses (overburden stress and maximum and minimum horizontal in-situ stress) are very important parameters [20, 33]. For rock mechanical properties prediction, numerous empirical equations and the empirical equations of volcanic rock formation were introduced by Wu et al. [34]. For pore pressure prediction, the equivalent depth method, Eaton’s method, modified Eaton’s method, effective stress method, Bowers’ method, Miller’s method, Tau’s method, Zhang’s method, and Eberhart–Phillips’ method can be used [35-37]; the effective stress method was used in this paper. For in-situ stresses prediction, the in-situ stress model proposed by Blanton and Oison [38] was utilized. The burial depth of Permian volcanic formation in Sichuan Basin ranges from 5000 m to 6500 m, and the reservoir thickness is approximately 250 m. YT-1 well is an exploration well of Permian volcanic formation in Sichuan Basin. According to the logging interpretation method, the logging data of Section 5640–5760 m in YT-1 well are interpreted, and the 1D MEM of Permian volcanic formation was obtained (Figure 1). From left to right, the first track is the pore pressure profile, the second track, the maximum horizontal in-situ stress profile; the third track, the minimum horizontal in-situ stress profile; the fourth track, the cohesive strength profile; the final track, the internal friction angle profile. The maximum horizontal in-situ stress is approximately 154–170 MPa, the minimum horizontal in-situ stress is approximately 121–140 MPa, the pore pressure is approximately 92–106 MPa, the cohesive strength is approximately 19–44 MPa, and the internal
friction angle is approximately 31–44°. In the interval of 5640–5760 m, substantial changes in pore pressure, maximum horizontal in-situ stress, minimum horizontal in-situ stress, cohesive strength, and the internal friction angle occurred. In other words, the spatial variability of in-situ stresses and rock properties in this interval is very significant. The 1D MEM confirmed that the Permian volcanic formation is featured by strong heterogeneity and strong uncertainty.

Figure 1. 1D MEM of Permian volcanic formation for YT-1 well.

4. Results and Discussions

4.1. Uncertainty of input parameters

The Permian volcanic rocks in the Sichuan Basin are featured by complex lithology and strong heterogeneity, and the uncertainty of mechanical parameters has a significant effect on the stability of the borehole wall. To analyze the effect of uncertainty, we first clarified the distribution characteristics and uncertainties of input parameters. On the one hand, the uncertainty originates from the spatial variability caused by the complex lithology and heterogeneity of volcanic rocks; on the other hand, it stems from the logging response and interpretation errors. The uncertainty of the input parameters will directly affect the predicted results of collapse pressure. In general, the stronger the uncertainty of the input parameters, the wider their is, and the more significant the effect on the predicted results of collapse pressure. Thus, we fitted and determined the distribution types of random variables and the uncertainty parameters for Permian volcanic rocks in YT-1 well. In general, the distribution types of random variables can be divided into different probability distribution types, such as the uniform, triangular, normal, lognormal, Weibull, logistic distribution, loglogistic, InvGauss distribution, and so on [31-32]. According to the logging interpretation results in Figure 1, the distribution fitting method of random variables was used to determine the distribution types and its characteristic parameters. The optimal fitting results of in-situ stresses and rock strength are shown in Figure 2, where the optimal fitting results of maximum horizontal in-situ stress, minimum horizontal in-situ stress, cohesive strength, and internal friction angle are given. Table 1 lists all the fitting results of MEM parameters used for wellbore stability analysis and the optimal distribution type and characteristic parameters. The
cohesive strength, internal friction angle, and maximum and minimum horizontal in-situ stresses conform to the loglogistic and InvGauss distribution, respectively, whereas the pore pressure conforms to the Weibull distribution.

![Histograms of random variables](image)

**Figure 2.** Fitting results of random variables for Permian volcanic formation.

**Table 1.** Statistical results of random variables for Permian volcanic formation.

| No. | Parameter                              | Distribution | Mean    | Standard deviation | $P_5$   | $P_{95}$  |
|-----|----------------------------------------|--------------|---------|--------------------|---------|-----------|
| 1   | Maximum horizontal in-situ stress / MPa | Loglogistic  | 159.58  | 1.43               | 155.59  | 167.38    |
| 2   | Minimum horizontal in-situ stress / MPa | InvGauss     | 131.16  | 2.76               | 128.61  | 137.62    |
| 3   | Pore pressure / MPa                    | Weibull      | 99.10   | 2.17               | 93.30   | 103.98    |
| 4   | Cohensive strength / MPa               | Loglogistic  | 27.49   | 4.55               | 20.48   | 37.56     |
| 5   | Internal friction angle / °             | Loglogistic  | 36.66   | 2.63               | 33.62   | 42.30     |

4.2. Risk assessment results of wellbore collapse

To quantitatively assess the collapse risk of Permian volcanic formation, we included the uncertainty of random variables in the present paper, and the collapse risk and probability were quantitatively
determined using uncertainty assessment modeling. Based on the random variables given in Table 1, the Monte–Carlo simulation was carried out to quantitatively calculate the collapse risk of Permian volcanic formation in TY-1 well, and the result is shown in Figure 3. The probability density distribution and cumulative probability distribution of wellbore collapse are given in Figure 3. The equivalent mud weight (EMW) of critical collapse pressure mainly ranges from 1.5 g/cm³ to 1.9 g/cm³, the maximum EMW of collapse pressure is approximately 2.0 g/cm³, and the minimum EMW of collapse pressure is approximately 1.4 g/cm³. The assessment results are consistent with the characteristics of complex lithology, strong heterogeneity, and strong uncertainty of Permian volcanic formation. To ensure the wellbore stability of Permian volcanic formation, we determined the EMW of critical collapse pressure with a sufficient probability of wellbore stability. Considering the actual drilling experiences, the allowable reliability probability of 80%–95% depends on both technological and economic levels. According to the assessment results, the EMWs of critical collapse pressure are 1.79, 1.81, 1.84, and 1.88 g/cm³ for the reliability probability of 80%, 85%, 90%, and 95%, respectively. In other words, the higher the reliability probability, the lower the risk of wellbore collapse and the higher the EMW of critical collapse pressure required. For the actual drilling operation of YT-1 well, the required EMW of critical collapse pressure is approximately 1.88 g/cm³ for the reliability probability of 95%. However, the actual EMW of wellbore pressure ranges from 1.32 g/cm³ to 2.23 g/cm³ during drilling, completing, and testing; this value is lower than the required EMW of critical collapse pressure of 1.88 g/cm³. A huge risk of wellbore collapse was observed. A large amount of chippings and debris were found in annulus, testing string, and surface equipment during completing and testing, Consequently, the testing string and surface equipment were blocked, and the YT-1 well was forced to stop testing operation. Thus, the assessment results are consistent with the actual situation of YT-1 well.

![Figure 3. Probability density and cumulative probability of wellbore collapse for YT-1 well.](image)

4.3. Parameter sensitivity analysis of wellbore collapse

Parameter sensitivity analysis is helpful in understanding the sensitivity degree of input parameters on wellbore collapse. When performing parameter sensitivity analysis, only the average value of a certain parameter is changed, and the other parameters remain unchanged. The present paper changed the average value of each basic parameter by ±10%, whereas the change value of EMW of the critical collapse pressure was calculated under the reliability of 90%. Figure 4 shows the parameter sensitivity analysis result. The EMW of critical collapse pressure is positively correlated with the maximum
horizontal in-situ stress and pore pressure, that is, the EMW of critical collapse pressure increased with the increase in maximum horizontal in-situ stress and pore pressure. The EMW of critical collapse pressure is negatively correlated with the minimum horizontal in-situ stress, cohesive strength, and internal friction angle, that is, the EMW of critical collapse pressure decreased with the increase in the minimum horizontal in-situ stress, cohesive strength, and internal friction angle. The most sensitive factor affecting the wellbore stability was the maximum horizontal in-situ stress, followed by pore pressure, internal friction angle, cohesive strength, and minimum horizontal in-situ stress. Thus, the order of the sensitivity ranking of wellbore stability parameters is as follows: maximum horizontal in-situ stress > pore pressure > internal friction angle > cohesive strength > minimum horizontal in-situ stress. Thus, the maximum horizontal in-situ stress and pore pressure of Permian volcanic formation must be determined to ensure the accuracy of wellbore stability analysis. In addition, the present method and the results can provide theoretical guidance for the prevention and treatment of wellbore collapse incidents for Permian volcanic formation.

![Tornado diagram of parameter sensitivity analysis.](image)

**Figure 4.** Tornado diagram of parameter sensitivity analysis.

5. **Conclusions**

In view of the complex lithology, strong heterogeneity, and strong uncertainty of Permian volcanic formation, the reliability assessment theory was used to quantitatively assess the collapse risk, and the following conclusions were drawn:

1. Combined with the logging data and interpretation methods, the 1D MEM was proposed. The uncertainty of MEM was assessed by fitting the logging interpretation results, and the findings results indicated that the cohesive strength, internal friction angle, and maximum horizontal in-situ stress conformed to a loglogistic distribution, the minimum horizontal in-situ stress conformed to the InvGauss distribution, whereas the pore pressure conformed to the Weibull distribution.

2. The risk assessment results of wellbore collapse for the YT-1 well indicated that the EMW of critical collapse pressure was approximately 1.88 g/cm³ when the collapse risk was 5% (i.e., reliability 95%), whereas the EMW of the well testing fluid ranged from 1.32 g/cm³ to 2.23 g/cm³. Therefore, the EWM of well testing fluid was lower than 1.88 g/cm³. Consequently, a serious sand production
problem blocked the annulus and testing string, resulting in a failed perforation test. The actual field results are in good agreement with the risk assessment findings.

(3) The collapse pressure of the Permian volcanic formation in the YT-1 well is positively correlated with the maximum horizontal in-situ stress and pore pressure, whereas it is negatively correlated with the minimum horizontal in-situ stress, cohesive strength, and internal friction angle. The parameter sensitivity ranking of the collapse pressure for the Permian volcanic formation is as follows: maximum horizontal in-situ stress > pore pressure > internal friction angle > cohesive strength > minimum horizontal in-situ stress. Thus, complex geo-mechanical parameters are the main factors affecting the wellbore collapse of the Permian volcanic formation in Sichuan Basin.

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