Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 9, No. 2, 2025
www.scholink.org/ojs/index.php/asir

Original Paper

Research Progress and Prospect of Well Leakage Intelligent Identification and Monitoring Technology

Lihao Zhou[1] & Chi Zhao[1]

[1] College of Petroleum Engineering, Xi'an Shiyou University, Xi'an 710065, China

Received: February 20, 2025   Accepted: March 12, 2025   Online Published: March 22, 2025
doi:10.22158/asir.v9n2p1   URL: http://doi.org/10.22158/asir.v9n2p1

Abstract

Well leakage is a major factor affecting the safety of drilling operations, especially for fractured reservoirs. At present, scholars at home and abroad have carried out a lot of research on the causes of well leakage, leakage identification, leakage prevention process and other aspects, and have made great progress, but there are few systematic summaries on the intelligent monitoring of well leakage. Therefore, the research on the existing well leakage intelligent monitoring technology is of guiding significance to the subsequent development of well leakage monitoring technology by understanding the mechanism, technical method and effect achieved by each well leakage monitoring technology. Based on the systematic summary of the causes of well leakage and the factors affecting leakage loss, it focuses on the common methods of well leakage intelligent monitoring both at home and abroad, and summarises the evaluation effect of the methods and proposes the development trend and research focus of the well leakage intelligent monitoring technology. The development trend and research focus of intelligent monitoring technology are proposed.

Keywords

Well leakage, Monitoring technology, Machine learning, Neural network

1. Introduction

In the process of oil and gas exploration and development in China, drilling often encounters fractured reservoirs, resulting in well leakage accidents, which not only prolongs the drilling cycle and loss of mud, but also may cause a series of complex situations such as stuck drilling, blowout, and well-wall instability, which may lead to the scrapping of the borehole in serious cases and cause significant economic losses, therefore, an in-depth understanding of the mechanism of well leakage from the geological and engineering factors is of important significance to the study of the well leakage monitoring method (Zhang et al., 2022; Deng et al., 2023; Hou et al., 2024). Therefore, in-depth understanding of the mechanism of well leakage from geological and engineering factors is of great significance to the study of well leakage monitoring methods. At present, scholars at home and abroad have carried out a lot of research on the causes of well leakage, leakage identification, leakage prevention process and other aspects, and have made great progress, but there are few systematic summaries on the intelligent monitoring of well leakage (Chen et al., 2023; Zheng et al., 2023; Zhou et al., 2024). Therefore, it is of guiding significance for the development of subsequent well leakage monitoring technology to investigate the existing well leakage intelligent monitoring technology, and to understand the mechanism, technical method, and the effect achieved by each well leakage monitoring technology.

2. Types of Well Leakage

Well leakage is a common downhole complication in which various working fluids directly enter the formation due to differential pressure imbalance and improper drilling process during drilling operations, and is characterised by a significant high incidence in fractured reservoirs. The root cause of well leakage is that the fluid column pressure in the well is higher than the formation pressure. Based on this, a number of scholars have proposed different classification methods for well leakage, as shown in Table 1.

Table 1. Types of Well Leaks

number	author	Classification principles	typology
1	Wang Yezhong et al.	Leakage mechanisms in fractured reservoirs	Natural fractured reservoir leakage, induced fractured reservoir leakage
2	Xue Jiu Huo et al.	Leakage velocity	Micro leakage, small leakage, medium leakage, large leakage, severe leakage
3	Wang Tao et al.	Stratigraphic features	Pore leakage, fissure leakage, cavernous leakage
4	Li Wenzhe et al.	Drilling fluid leakage mechanism	Fracture leakage, closed-fracture extensional leakage, differential pressure leakage
5	Bi Shubo	Leakage channel	Single leakage system, composite leakage system
6	Shi Xiaoyan et al.	Subjective and objective factors	Natural, man-made losses

Wang Yezhong et al. (2007) subdivided fractured reservoir leakage into natural fractured reservoir leakage and induced fractured reservoir leakage based on fractured reservoir leakage mechanism analysis. Xue Juhuo et al. (2016) classified well leakage into micro leakage (leakage rate 5m3/h), small leakage (leakage rate 5-15m3/h), medium leakage (leakage rate 15-30m3/h), large leakage (leakage rate 30-60m3/h), and severe leakage (leakage rate 60m3/h) according to leakage rate. Wang Tao et al. (2021) addressed the well leakage problem under complex geological conditions in Tarim oilfield, combined with stratigraphic characterisation to analyse the well leakage types in the field, and classified them into three categories: pore leakage, fracture leakage and cavern-type leakage. In their study of well leakage in Changning Block, Sichuan Province, Li Wenzhe et al. (2022) classified the common drilling fluid leakage mechanisms in deep brittle shale into three types: fracture leakage, closed-fracture extension leakage, and differential pressure leakage, and gave a leakage pressure prediction model for different leakage types. Bi Shubo (2023) further classified well leakage according to the leakage channels into two categories: single leakage system and composite leakage system, where the single leakage system includes pore, fracture, and cavern types, and the composite leakage system includes pore-fracture, fracture-cavern, and pore-seam-cavern. Shi Xiaoyan et al. (2023) classified well leakage into natural and man-made leakage according to the subjective and objective factors of well leakage, in which natural leakage can be further subdivided into three types: pore leakage, natural fracture leakage, and cavern leakage.

3. Causes of Well Leakage

In 2009, Yang Xianzhang et al. investigated and researched the well leakage situation of exploration wells in Kucha depression, and found that the fundamental reason for the frequent occurrence of well leakage in Kucha block lies in its complex geological structure, which is manifested in the development of large fracture tectonic zones in front of the mountain, the deposition of shallow, weakly cemented gravel layer, and the extensive expansion of the fracture system of the destination layer, and the formation of multi-stage leakage channels through different mechanisms. occurrence of well leakage accidents. And Kang Yili et al. (2013) found that geological factors are the internal factors causing well leakage accidents based on the analysis of leakage main control factors, and the drilling process is also another major factor causing well leakage. Liu Xinran (2019), in the process of studying the causes of leakage in the leaky layer of Linfen block, found that the most important reason for the frequent occurrence of well leakage in Linfen area is geological reasons, i.e., the formation is weak in pressure bearing, bad in diagenesis, serious in weathering, and unstable in structure, and also the poor performance of drilling fluids may be one of the direct causes of well leakage. Zhang Xuliang et al. (2023) found that the agitation pressure during drilling will have a greater impact on well leakage by studying the effect of agitation pressure on leakage, and different types of drilling tools produce different agitation pressures, resulting in different levels of risk, shorter drill columns falling into the well produce smaller agitation pressures, and longer drill columns falling into the well will produce larger agitation pressures. Based on this, Li Zhankui et al. (2024) concluded that there are two main categories of causes of well leakage: geological factors and drilling process factors.

According to the above literature research, the current understanding of the causes of well leakage mainly focuses on the two categories of geological factors and drilling process. Geological factors mainly lie in the following three aspects. 1. Fracture and cavern development in the formation, the natural fracture and cavern development provides a fast leakage channel for the working fluid to leak out during the drilling process. 2. Complicated formation lithology, in the formation with high porosity and high permeability such as sandstone, conglomerate, or unconsolidated loose formation, the drilling fluid will slowly penetrate into the pore space under the effect of differential pressure, thus generating well leakage. In addition, reservoirs with lithology such as carbonate rock and granite, whose internal cavities and cracks are often developed, are prone to drilling fluid leakage. 3. Abnormal formation pressure, the existence of multiple pressure systems in the same well section, and the difficulty of taking the density of drilling fluid into account, lead to the leakage of low-pressure formations.

The drilling process leading to well leakage accidents mainly includes improper design of drilling parameters, poor performance of drilling fluid and well leakage caused by other special processes. 1. The influence of drilling parameter design, when the drilling speed or rotational speed is too high, it will aggravate the perturbation of drilling tools and thus cause the expansion of cracks in the wall of the well, and the irrational design of the structure of the well body will lead to the difficulty in controlling the density of drilling fluid. 2. The influence of the performance of the drilling fluid, when the drilling fluid density is too high, the column pressure will be too high, which will lead to the development of low-pressure layer leakage. 3. When the drilling fluid density is too high, the column pressure will exceed the fracture pressure of the formation or the pressure-bearing capacity of natural fractures/pores, fracturing the formation or aggravating the opening of leakage channels. When the density is too low, it may cause the well wall to collapse, forming new fractures or enlarging existing ones, indirectly inducing leakage. 4. The influence of other special processes, such as underbalanced drilling, cementing, and well workover operations, etc., all have the risk of leading to well leakage.

4. Conventional Well Leakage Monitoring Techniques

Usually, scholars at home and abroad mainly establish corresponding pressure prediction models based on conventional physical laws through the principle of leakage and its influencing factors to achieve the identification and monitoring of well leakage. In this regard, China has a late start in well leakage monitoring technology. 1996, Lietad et al. established a computational model for the radial leakage of Bingham fluid in an infinitely long fracture based on the theorem of momentum conservation and the pressure drop generated by the flow of drilling fluid in the fracture. Safillippo et al. (1997) established a radial leakage model for the drilling fluid in a fracture of infinite length assuming that an infinitely long fracture and only one of them are intersected with the wellbore, and that a laminar movement of a Newtonian type of fluid was established. A model for radial leakage of drilling fluid was developed. On this basis, Maglione et al. (1997) established a drilling fluid leakage model for the Bingham flow pattern, taking into account the effects of fracture width, total leakage, drilling fluid viscosity, wellbore diameter, and pressure difference between the wellbore and the formation, etc. In 2004, Lavrov et al.

(2004) focused on the effect of fracture width, assuming that a finite-length fracture, with the change of the fracture width to meet the linear law In 2004, Lavrov et al. focused on the influence of fracture width and assumed that the fracture of finite length and the change of fracture width with the change of fracture width satisfied the linear law, and the flow pattern of drilling fluid was a power law pattern, so they established the radial leakage model of single fracture considering the influence of formation pressure, fracture width, length, drilling fluid rheology, drilling fluid density, wellbore radius, etc. In 2006, Majidi et al. found that the Hepa fluid has the representativeness and universality that the other rheological models don't have, and so they established H-B leakage model, which has many fewer defects compared with the other rheological models. B model has fewer defects.In 2011, Jiang Hongwei et al. proposed a formation very small leakage pressure model and gave the relationship between the leakage differential pressure and formation pore pressure and fracture pressure, which can well monitor well leakage and judge the type of leakage.In 2014, Zou Deyong et al. established a leakage pressure model with and without mudcake based on the fluid constitutive equations and the capillary seepage theory, respectively.2024. In 2024, Chen Ganghua et al. established a new method for identifying well leakage layers based on the basic conditions of well leakage and combined with the mechanical properties and physical mechanisms of the leakage layer, which can well predict the well leakage in permeable formations. Table 2 shows the conventional well leakage monitoring methods.

Table 2. Conventional Well Leakage Monitoring Methods

author	modelling equation	note
Lietad et al.	$\frac{dp}{dr}=\frac{12\mu_p v}{w^2}+\frac{3\tau_y}{w}$	Where, v-mean fluid velocity inside the crack; p-fluid pressure; r-radial distance; μp-plastic viscosity; yτ-dynamic shear force; w-crack width
Safillippo et al.	$\frac{1}{r}\frac{1}{\partial r}\left(r\frac{\partial p}{\partial r}\right)=\frac{\mu c_t\phi_f}{k_f}\frac{\partial p}{\partial t}$	Where, p-fluid pressure; r-radial distance; μ-apparent viscosity of drilling; tc-composite compression coefficient; kf-permeability; ϕf-porosity
Maglione et al.	$\Delta p(t)=\frac{6Q\mu}{\pi w^3}ln\frac{\left[\frac{V(t)}{\pi w}+{r_w}^2\right]^{\frac{1}{2}}}{r_w}$	Where, Q-leakage rate; Δp(t)-differential pressure at moment t; rw-borehole radius; μ-drilling fluid viscosity; w-fracture width

Lavrov et al.	$\left(\frac{n}{2n+1}\right)\left(\frac{1}{k}\right)^{\frac{1}{n}}\frac{w^{2+\frac{1}{n}}}{2^{1+\frac{1}{n}}}\frac{1}{r}\frac{\partial p}{\partial r}\left\|-\frac{\partial p}{\partial r}\right\|^{\frac{1}{n}} + \left(\frac{n}{2n+1}\right)\left(\frac{1}{k}\right)^{\frac{2}{n}}\frac{1}{2^{1+\frac{1}{n}}}\frac{\partial}{\partial r}\left(w^{2+\frac{2}{r}}\frac{\partial p}{\partial r}\left\|-\frac{\partial p}{\partial r}\right\|^{\frac{2}{r}}\right) = -\frac{\partial w}{\partial t}$	Where, w-local fracture aperture; K-consistency index
Majidi et al.	$-\frac{dp}{dr} = 2\left(\frac{2n+1}{\pi n}\right)^{n}\frac{kq^{n}}{w^{2n+1}r^{n}} + \left(\frac{2n+1}{n}\right)\left(\frac{2\tau_y}{2}\right)$	Where, dp/dr-pressure gradient; q-flow rate; w-fracture hydraulic width
Jiang Hongwei et al.	$P_{Lpmin} = (\sigma_v - \sigma_{ep})/\emptyset$	Where, Plpmin-natural very small leakage pressure
Zou Deyong et al.	$p_l = p_P + \frac{3q_f\mu}{2\pi Kh}ln\frac{r_f}{r_w} + 4\tau_0(r_f - r_w)\sqrt{\frac{\emptyset}{2K}}$	No mud cake case, where, qf-drilling fluid leakage flow rate; h-thickness of the leakage layer; K-permeability of the formation; Δpc-pressure drop in the intrusive zone of the formation; μ-plastic viscosity of the drilling fluid; rw, rf-radius of the borehole and the intrusive zone; τ0-yielding value of the drilling fluid
Zou Deyong et al.	$p_l = p_P + \frac{q_f}{2\pi h}(\frac{\mu_f}{K_m}ln\frac{r_w}{r_m} + \frac{\mu_f}{K_n}ln\frac{r_n}{r_w})$	In the case of mudcake, Km and Kn are the permeability of mudcake and plug layer, respectively; rw,rm and rn are the radius of the original borehole, the borehole with mudcake and the plug layer, respectively; μf is the apparent viscosity of the drilling fluid filtrate
Chen Ganghua et al.	$\xi = (6r - D_{50})\left(\alpha_{\Delta p}\frac{\Delta p - \Delta p_{min}}{\Delta p_{max} - \Delta p_{min}} + \alpha_{\phi}\frac{\phi - \phi_{min}}{\phi_{max} - \phi_{min}} + \alpha_K\frac{lnK - lnK_{min}}{lnK_{max} - lnK_{min}}\right)$	Where, ξ-well leakage composite index; r-mean pore throat radius of the formation; D50 is the particle size corresponding to the cumulative mass fraction of the solid phase particle size of the drilling fluid at 50%; Δpmax,

		Δpmin-maximum and minimum values of the leakage differential pressure; ϕmax, ϕmin-maximum and minimum values of the porosity, minimum values; Kmax, Kmin-maximum and minimum values of permeability; αΔp, αϕ, αK-weights of differential leakage pressure, porosity and permeability.

5. Intelligent Monitoring Technology for Well Leakage Based on Machine Learning

With the continuous rise of intelligent algorithms, the combination of oil and gas exploration and development field and artificial intelligence technology is getting closer and closer, and Chinese and foreign scholars have proposed many well leakage intelligent prediction methods, which provide a new way to predict well leakage accidents. Compared with traditional methods, well leakage intelligent monitoring methods can respond to the occurrence of well leakage accidents more timely and accurately, and reduce the influence of human judgement, which has a good application prospect. At present, the well leakage intelligent monitoring technology can be divided into two categories based on its model structure and algorithm principle, namely, non-neural network-based well leakage intelligent monitoring method and neural network-based well leakage intelligent monitoring method.

5.1 Intelligent Monitoring Method for Well Leakage Based on Non-neural Network

Non-neural network is a traditional machine learning method distinguished from neural network, which does not rely on multi-layer neuron structure to automatically extract features, but constructs the prediction mechanism through explicit mathematical models or statistical laws, and typical non-neural network algorithms include linear regression, support vector machine, decision tree, and plain Bayes.

In 2018, Li et al. found that by comparing three machine learning algorithms, namely BP neural network, support vector machine, and random forest, in well leakage prediction, the random forest algorithm has a higher prediction accuracy when the input parameters are 12 parameters such as drilling conditions, drilling fluid performance, and formation rock properties, while the support vector machine has a poorer accuracy. Based on this, Liu Biao et al. (2019) improved the support vector machine model and proposed a well leakage early warning model based on support vector regression, and the field application found that the model was able to predict well leakage conditions during drilling wells well qualitatively and quantitatively.In 2020, Shi Xiaoyan et al. established a well leakage early warning model through the Random Forest method and screened out the pressure, well depth, inlet flow rate and other 10 strongly related input parameters, and accurately predicted the complex well leakage accidents in Tarim Oilfield. Chen Kaifeng et al. (2022) compared four algorithms, namely, random forest, support vector machine, BP neural network and logistic regression, in the direction of intelligent prediction of well leakage and found that, compared with the other three algorithms, the random forest model was able to accurately identify well leakage well segments to meet the needs of on-site engineering and had an accuracy of up to 98%, which further verified the advantages of the random forest in the monitoring of well leakage. Xin Wang et al. (2022) proposed a well leakage prediction method with an improved sparrow search algorithm for optimising the support vector machine, which used the improved sparrow search algorithm to optimise the penalty parameter C and kernel parameter g of the support vector machine (ISSA-SVM) for the prediction of well leakage accidents, and achieved a large improvement in the prediction accuracy and computation time. Based on this, Bai et al. (2024) proposed an improved random forest algorithm based on the M5 model tree and established an ISSA-IRF well leakage prediction model based on the improved sparrow search algorithm, which further improved the well leakage prediction model accuracy and robustness. In summary, the Random Forest algorithm for predicting well leakage accidents is a very effective prediction method in many cases, and the Random Forest-based multi-machine learning method will become the main development direction in the future.

5.2 Intelligent Monitoring Method for Well Leakage Based on Neural Network

In recent years, more and more scholars have found that neural network algorithms have good application effects in well leakage monitoring. Neural network is a machine learning algorithm based on artificial neurons, which consists of a large number of neuron nodes interconnected with each other, and these nodes are connected to each other in the network, which can deal with complex data inputs and perform various classification and regression tasks. Compared to non-neural networks, neural network algorithms have a larger amount of data processing and greater data processing capabilities.

In 2018, Agin et al. established a well leakage prediction model based on an adaptive neuro-fuzzy inference system and used data mining techniques to analyse the drilling data to determine the characteristic parameters that have a greater impact on the occurrence of well leakage accidents, which improves the accuracy of well leakage prediction. Aljubran et al. (2021) established a well leakage accident prediction model based on deep learning and time series analysis. The results showed that the use of one-dimensional convolutional neural network can effectively predict well leakage accidents. Song Yan et al. (2022) proposed a well leakage intelligent monitoring model based on limit learning machine, and optimised the limit learning machine by sparrow search algorithm to further improve the convergence speed and accuracy of the model. Luo Ming et al. (2023) proposed a prediction method based on deep convolutional feature reconstruction network for the prediction of well leakage accidents in offshore oil drilling, which screened the key parameters through the ReliefF algorithm, constructed the sliding-window inner-product feature matrix, learnt the features of the normal working conditions by using the convolutional network, and achieved the accident warning based on the reconstruction error. The method breaks through the limitations of traditional methods in highly dynamic and non-periodic data. Li Zhengkang et al. (2023) compared three typical neural networks backpropagation neural network (BP), convolutional neural network (CNN) and long-short-time neural network (LSTM) in well leakage identification, and the results showed that LSTM can learn more hidden features and have higher well leakage identification rate compared to the other two neural networks. On this basis, Dong Abing et al. (2024) proposed a CNN-LSTM fusion model, which combines the local feature extraction capability of CNN and the temporal feature processing capability of LSTM to achieve real-time warning of well leakage risk and querying of historical data, which provides a practical tool for drilling sites.

6. Summary

The main problems that need to be paid attention to and to be solved in the research on the intelligent monitoring technology of well leakage are as follows.

(1) The application of machine learning algorithms such as neural networks can monitor well leakage well to a certain extent, but the accuracy and timeliness of monitoring still need to be further improved, so exploring machine learning algorithms with higher accuracy and timeliness is one of the future development directions.

(2) Machine learning often relies on a large amount of well leakage-related data, but the field data are often heavily fragmented, and data collection, screening and integration are difficult, and the problem of small data volume and small data types in the training set of algorithm models is becoming more and more prominent. Therefore, a large amount of well leakage data has to be collected by analysing more drilling logs to enrich the neighbouring well leakage database and further test and improve the model.

(3) At present, the practicality of intelligent algorithms often varies for different working conditions or geological situations. Therefore, the development of a complete well leakage monitoring system has become an important task for future research.

Acknowledgements

This work might not be possible without financial support from the Xi'an Shiyou University Students' Innovation and Entrepreneurship Training Program Funded Project (No. 202310705049).

References

Agin, F., Khosravanian, R., Karimifard, M., & Jahanshahi, A. (2018). *Application of adaptive neuro-fuzzy inference system and data mining approach to predict lost circulation using DOE technique* (case study: Maroon oilfield). Petroleum.

Aljubran, M., Ramasamy, J., Albassam, M., & Magana-Mora, A. (2021). Deep Learning and Time-Series Analysis for the Early Detection of Lost Circulation Incidents During Drilling Operations. *IEEE Access*, *9*, 76833-76846. http://doi.org/10.1109/ACCESS.2021.3082557

Bai, K., Dai, S., Zhang Zhaoshuo, & Jin, S., Yi. Optimisation of swarm intelligence algorithm to improve random forest algorithm for well leakage prediction. *Modern Electronic Technology*, 1-9.

Bi Shubo. (2023). *Study on Leakage Mechanism of Fractured Formation* (Master's Thesis, Changjiang University).

Chen Ganghua, He Yulong, Qiu Zhengsong, Key, & Wang Xiaojun. (2024). Research and application of fine identification method of well leakage characteristics during drilling process. *Oil Drilling Technology*, *52*(01), 26-31.

Chen, K. F., Yang, X. W., Song, X. Z., Chen, D., Zhang, W., Han, L., & Xing, S.. (2022). Intelligent Diagnosis of Well Leakage Based on Engineering Logging Data. *Petroleum Machinery*, *50*(11), 16-22.

Chen, L., Lu, H. E., Wang, Z. H., Li, C. C., Yang, H., Zhang, M. X., & Xu, T. T.. (2023). Determination of well leakage type and analysis of controlling factors by integrating Light GBM and SHAP. *Drilling and Completion Fluids*, *40*(06), 771-777.

Deng Jinhui, Tan Zhongjian, Yuan Yadong, Zhang Qianqian, & Peng Chao. (2023). Characteristics and mechanical mechanism of Paleoproterozoic-Neoproterozoic fissure leakage fracture system in the Bohai Sea. *China Petroleum Exploration*, *28*(05), 84-98.

Detao Zhou, Chenzhan Zhou, Ziyue Zhang, Mengmeng Zhou, Chengkai Zhang, Lin Zhu... & Chaochen Wang. (2024). Intelligent Lost Circulation Monitoring Method Based on Data Augmentation and Temporal Models. *Processes*, *12*(10), 2184-2184.

Dong A-Bing. (2024). *Deep Neural Network Based Well Leakage Risk Monitoring Method* (Master's Thesis, Changjiang University).

Hou Guanzhong, Xu Jie, Xie Tao, He Ruibing, Niu Xinpeng, & Huang Wei-an. (2024). Optimisation and application of high pressure unblocking and leakage prevention and plugging system in the fractured reservoir of Bozhong 19-6 submerged mountain. *China Offshore Oil & Gas*, *36*(02), 149-158.

Jiang, H., Shilin, & Guo, Q. F. (2011). Study on the natural minimal leakage pressure of formations. *Drilling and Completion Fluids*, *28*(05), 9-11+95-96.

Kang Yili, Wang Haitao, You Lijun, & Du Chunzhao. (2013). Determination of drilling fluid leakage probability based on hierarchical analysis. *Journal of Southwest Petroleum University (Natural Science Edition)*, *35*(04), 180-186.

Lavrov Alexandre, & Johan Tronvoll. (2004). *Modeling Mud Loss in Fractured Formations*. Paper presented at the Abu Dhabi International Conference and Exhibition, Abu Dhabi, United Arab Emirates, October 2004.

Li Wenzhe, Yu Xingchuan, Lai Yan, Liu Houbin, Wen Wen, Zhang Zhen, & Wu Shenjian. (2022). Leakage mechanism and controlling factors of drilling fluid in deep brittle shale wells. *Special Reservoirs*, *29*(03), 162-169.

Li Zejun, Chen Mian, Jin Yan, Lu Yunhu, Wang Hanqing, Geng Zhi, & Shiming Wei. (2018). *Study on Intelligent Prediction for Risk Level of Lost Circulation While Drilling Based on Machine Learning*. Paper presented at the 52nd U.S. Rock Mechanics/Geomechanics Symposium, Seattle, Washington, June 2018.

Li Zhankui, Wu Liwei, Guo Mingyu, Xu Kun, Ma Fugang, & Li Wenlong. (2024). Research and application of integrated geological engineering technology for deep high-pressure wells in Bozhong Depression. *Oil Drilling Technology*, *52*(02), 194-201.

Li Zhenkang. (2023). *Machine Learning Based Well Leakage Risk Identification in Offshore Drilling* (Master's Thesis, China University of Petroleum, Beijing).

Lietard Olivier, Unwin Tessa, Guillot Dominique, & Mike Hodder. (1996). *Fracture Width LWD and Drilling Mud / LCM Selection Guidelines in Naturally Fractured Reservoirs*. Paper presented at the European Petroleum Conference, Milan, Italy, October 1996.

Liu Biao, Li Xiaoxiao, Li Shuanggui, Tan Jun, Wang Guohua, & Liu Hongbin. (2019). Well leakage prediction based on support vector regression. *Drilling Process*, *42*(06), 17-20+1-2.

Liu Xinran. (2019). *Research on the mechanism and experimental evaluation of leakage prevention and plugging in Edong area* (Master's thesis, China University of Petroleum (Beijing)).

Luo Ming, Li Shengyang, Peng Wei, & Zhou Zhuang. (2023). Well leakage prediction based on deep convolutional feature reconstruction. *Computer Simulation*, *40*(07), 82-88.

Maglione, R., & Marsala, A. (1997). *Drilling mud losses: problem analysis*. AGIP Internal Report (1997).

Majdi, R. (2006). *Modeling of yield-power-law type of drilling fluid losses in naturally fractured reservoirs*. TUDRP Advisory Board Meeting Report, The University of Tulsa, 2006, 11.

Sanfillippo, F., Brignoli, M., Santarelli, F. J., & Bezzola, C. (1997). *Characterization of Conductive Fractures While Drilling*. Paper presented at the SPE European Formation Damage Conference, The Hague, Netherlands, June 1997.

Shi Xiaoyan, Ji Yong, Cui Mang, Li Zhongming, & Zhao Fei. (2023). Automatic identification of drilling fluid leakage types based on symbolic aggregation approximation. *Petroleum Drilling Process*, *45*(06), 696-703. http://doiorg/10.13639/j.odpt.202302038

Shi Xiaoyan, Zhou Yingcao, Zhao Liping, & Jiang Hongwei. (2020). Random Forest-based real-time judgement of leakage. *Drilling Process*, *43*(01), 9-12+7.

Song Yan. (2022). *Research on Intelligent Identification Method of Well Leakage Risk State Based on Extreme Learning Machine* (Master's thesis, China University of Petroleum (Beijing)).

Wang Yezhong, Yili Kang, Lijun You, & Jiajie Liu. (2007). Leakage Mechanism and Control Technology in Fractured Reservoirs. *Drilling and Completion Fluids*, (04), 74-77+99.

Wang, T., Liu, F. Z., Luo, W., Yan, Z. H., Lu, H. Y., & Guo, B. (2021). Progress and development of leakage prevention and plugging technology in Tarim Oilfield. *Oil Drilling Technology*, *49*(01), 28-33.

Wang, X., & Zhang, Q. Z. (2022). Improved sparrow search algorithm to optimise support vector machine for well leakage prediction. *Science, Technology and Engineering*, *22*(34), 15115-15122.

Xue Jiu-huo, Liu Qiang, Wang Xiang, & He Liu. (2016).An analysis of the causes of Paleozoic well leakage in MX10 well and suggestions. *Drilling and Mining Process*, *39*(01), 38-41+7-8.

Yang Xianzhang, Cai Zhenzhong, Lei Ganglin, Tang Yanguang, & Zhao Danyang. (2009). Geological characterisation of well leakage in the Kuqa depression. *Drilling Process*, *32*(03), 26-28+125.

Zhang Ou-Liang, Zhou Bo, Liang Shuang, Zhang Yao-Ming, Luo Fang-Wei, Wang Peng-Cheng, & Ren Hai-Fan. (2023). Analysis of factors affecting leakage due to agitation pressure. *Oil & Gas Chemistry*, *52*(03), 92-96.

Zhang Xiaocheng, Huo Hongbo, Lin Jiayu, Liu Hailong, & Li Jin. (2022). Geo-engineering integrated well leakage early warning technology for fractured reservoirs in Bohai Oilfield. *Oil Drilling Technology*, *50*(06), 72-77.

Zhang Zheng, Zhao Yu, Wang Jingpeng, Wang Guorong, Zhong Lin, Lu Jingsheng, & Yuan Jianpeng. (2023). A real time monitoring method for well-kick and lost circulation based on distributed fiber optic temperature measurement. *Geoenergy Science and Engineering*, 229.

Zou, D. Y., Zhao, J., Guo, Y. L., Fang, M. Z., & Guan, S. (2014). Leakage pressure prediction model for permeable sandstone formations. *Oil Drilling Technology*, *42*(01), 33-36.