Analysis on the Correlation between Water Injection in Salt Well and Induced Earthquake -- Taking the Changning Salt Well As an Example

Hao Ma[1, a], Mingxing Gou[2, b], Lingxin Sun[3, c], Jinlong Liang[4, d, *]

[1]School of Earth Sciences, Chengdu University of Technology, Chengdu, China

[2]School of Network Security, Chengdu University of Technology, Chengdu, China

[3]School of Environmental and Civil Engineering, Chengdu University of Technology, Chengdu, China

[4]School of Earth Sciences, Chengdu University of Technology, Chengdu, China

[a]987015672@qq.com, [b]1378379912 @qq.com, [c]940607348 @qq.com, [d]richardljl04@aliyun.com

*Corresponding author

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Abstract: The earthquakes induced by water injection are common at home and abroad. Some scholars have pointed out that water injection can directly cause or induce earthquakes. The relationship among water injection, earthquake, fracture and stress field have been studying. Based on the elastic callback theory, this paper described qualitatively and quantitatively the earthquake preparation processes induced by water injection into the salt wells in the Changning region in Sichuan, China. According to the earthquake induction mechanism established by Mohr-Coulomb criterion, the influence on the friction correlation coefficient and rock strength properties caused by imbalance of water injection into the salt wells was discussed, and the relationship between induced earthquake and salt well activities was established. A parameter model considering the influence factors of salt wells was introduced into the measurement of multiple seismic activity indexes. The spatio-temporal relationship between seismic activity index and salt well mining was obtained. Meanwhile, a Bayesian probability model for seismic risk assessment was established to assess the risk of the induced earthquakes. The results of this study are expected to provide a theoretical basis for other areas where water injection may induce earthquakes. It will provide a reference for the precaution of such earthquakes in the similar areas.

1. Introduction

In the 1930s, the increasing seismic activities after the completion of reservoirs was found abroad. In the early 1960s, an American munitions factory injected waste liquid into a deep well in Denver, and triggered a series of felt earthquakes. Since the 1970s, some Chinese oilfields of renqiu, shengli oilfield and other places have all experienced reduced earthquakes after oil and gas exploitation and high-pressure water injection [2-3]. Some microearthquakes are found to be directly related to water injection [4]. Renqiu earthquake research found that water injection can lead to cracks, but the leading cause is strong earthquakes. Water injection caused the rongchang earthquake and some small earthquakes, changed local seepage and void pressure, expanded the crack and leaded to large fracture [5]. According to the studies on the injecting water-induced Laomiaojun earthquake in yumen and the Zigong-longchang earthquake in sichuan, it can be seen that a large amount of fluid injection will cause inter-layer sliding and deformation uplift, but whether an earthquake occurs depends on local structural conditions [6-7]. The earthquakes were associated with the local shallow structure, water injection mode and water injection amount. It is an indisputable fact that water injection can directly cause or induce earthquakes. The relationship between water injection and earthquake, fracture and internal stress field changes in related areas is still being explored. Taking the induced earthquake in changning area as an example, this paper tried to explore the spatial-temporal relationship of water-induced earthquake and establish a risk assessment model.

2. Overview of water-induced earthquakes in changning area

Since April 2006, waterflood induced seismic activity has occurred in the intersection area of Changning, Xingwen, and Gongxian in Sichuan. According to effective statistics, from April 2006 to June 2019, more than 400 earthquakes occurred in Changning Window.

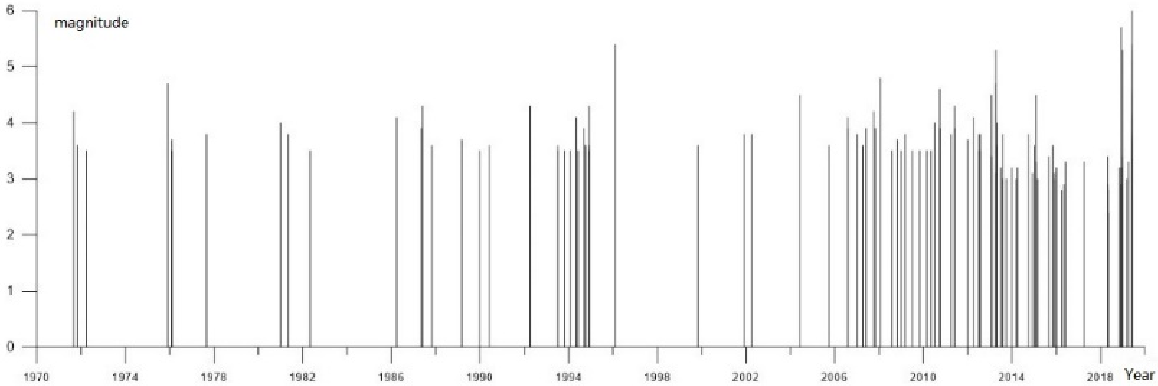

Figure. 1 m-t chart of earthquake magnitude in changning area from 1971 to 2019

There are few fixed stations in Yibin area, and the records of small earthquakes are weak, so the actual frequency of earthquakes in Changning area should be much higher than the current statistics.

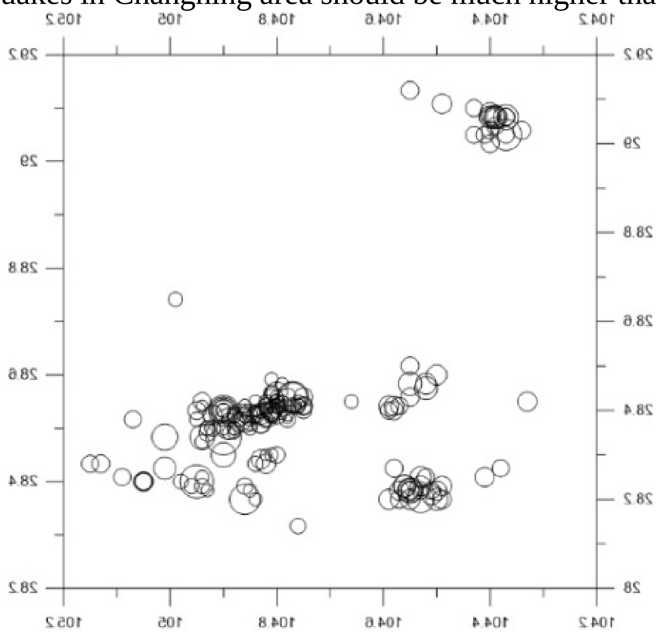

Figure. 2 1971-2019 changning window earthquake events (the bigger the bubble, the bigger the magnitude)

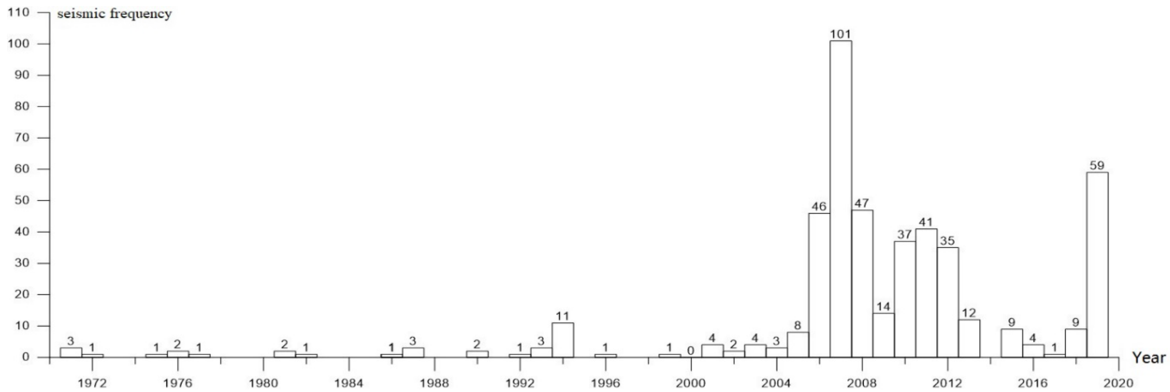

Figure. 3 Diagram of injection quantity and year of changning salt well

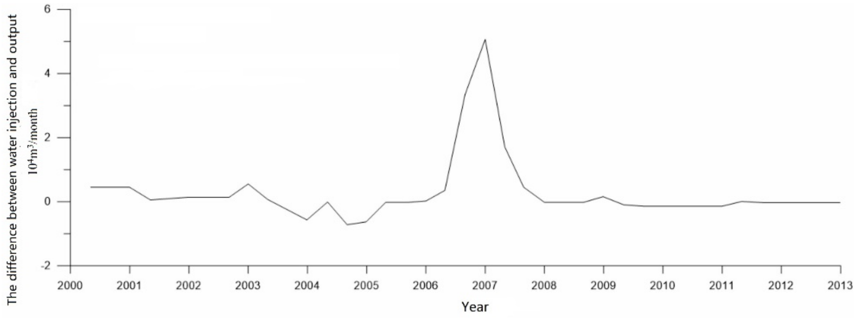

Figure. 4 Seismic frequency map of changning area from 1971 to 2019

On June 26, 2019, the seismic distribution in Changning window was concentrated in the Changning county and Gongxian county. It is found that before April 2006, when the mine water injection in Changning County is equal to the water output, the seismic activity is few. However, when the water injection far exceeds the water output, small and medium-sized earthquakes in shallow layers will be induced [8].

Some scholars have pointed out that a large amount of water injection for a long time may penetrate into small faults and micro-fracture zones in the anticline of Changning, accelerating the fracture of micro-tectonic strata in nearby areas and triggering small earthquake group activities [9].

The frequency of earthquakes in the Changning Window decreased after the injection - business trip to maintain a stable state. But in the first half of 2019, especially since June 17, 55 earthquakes occurred in just a few days. Among them, there were six medium-strong earthquakes with a magnitude of more than 5, and the largest one occurred on June 17, 2019 with a magnitude of ML 6.

3. Temporal and spatial relationship between earthquake and salt well mining activities

In order to discuss the temporal and spatial relationship between earthquakes and salt well mining activities, the earthquake magnitude, frequency, b value and focal depth in the Changning area were analyzed.

3.1 Time distribution characteristics

The relationship between known magnitude *M*, seismic frequency *N* and *b* value [10] is:

$$\lg N = a - bM \tag{1}$$

There is obvious correlation between the three indexes and the difference between injection and output. The increase of seismic frequency is obvious with the increase of the ratio of water injection to the output amount. And, the frequency, magnitude and b value of small and medium earthquakes in shallow layer increased abruptly after the sudden change of note-travel.

3.2 Spatial distribution feature

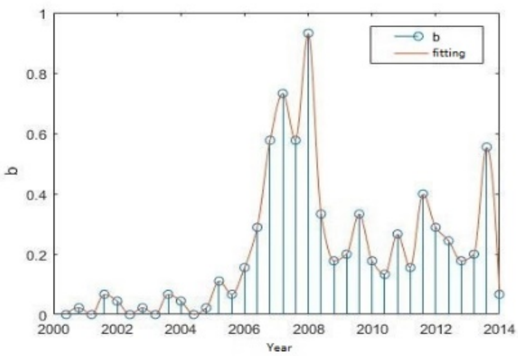

Figure. 5 Correlation curve between b value and year

Based on the geographical distribution of the epicentre from 1971 to 2019, the epicentre of the window mainly concentrated in Changning and Gongxian, showing obvious cluster distribution characteristics

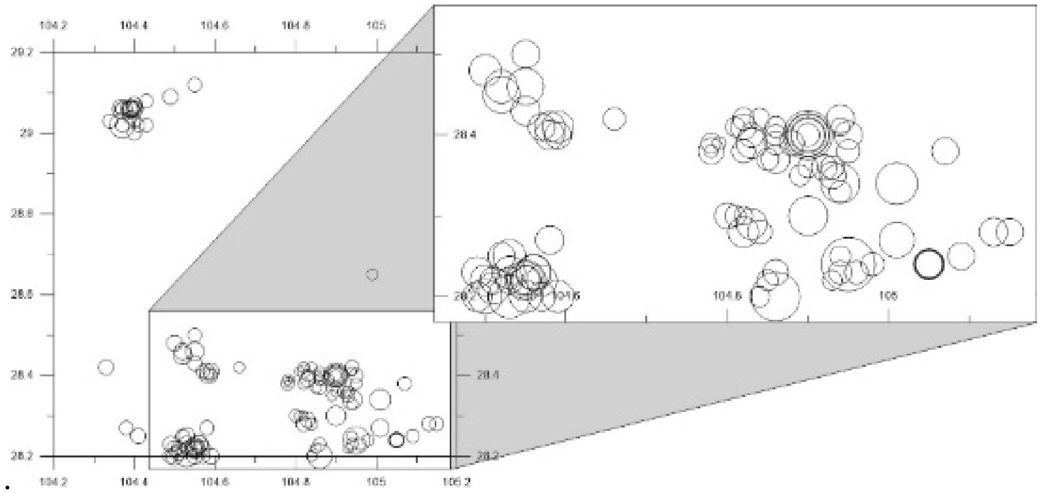

Figure. 6 Schematic diagram of changning window seismic profile (AB profile)

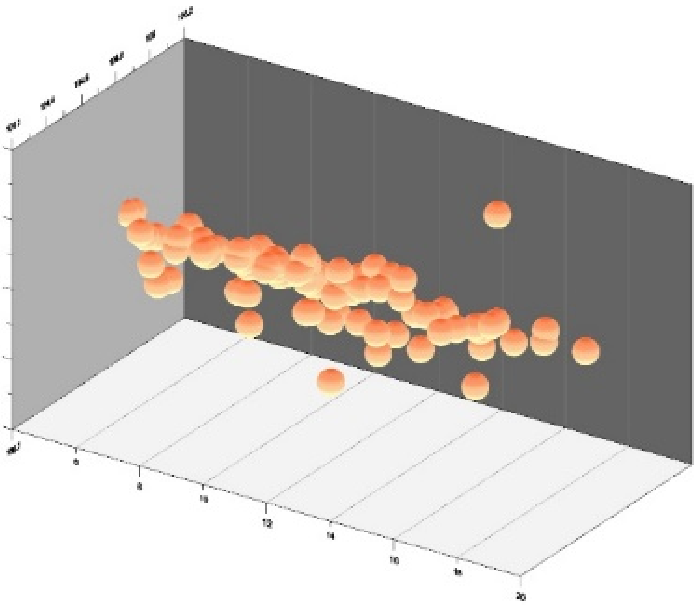

Figure. 7 2012.1-2019.3 source depth distribution map

Take the AB section of Changning as an example, from January 2012 to March 2019, the focal depth was mostly within 14m.The results show that the earthquakes in the Changning area are shallow earthquakes with small magnitude but high frequency. The the strong earthquake rarely occurred.

4. Analysis of water injection-induced seismic mechanism

4.1 Effects of salt well mining on seismic mechanism

Salt well mining will lead to stress redistribution around the wells. The diameter of the mine wells is generally not more than a few meters, and the mining is generally not near the structure plane. Therefore, the stress redistribution of salt well excavation has a rather weak influence on the induced earthquake.

Studies have shown that high-pressure water injection can lead to excess pore water pressure in rocks [11], and the effective stress decreases with the increase of pore water pressure.

The stress on the fault during sliding is:

$$P = \int_0^l \int_0^h \tau_n dydz \tag{2}$$

After considering mohr-coulomb criterion [13], the expression is:

$$p = \int_0^l \int_0^h (c + \sigma_n \tan\phi) dydz \tag{3}$$

$$= (C + \sigma_n \tan\phi)^2 \cdot h^2 l^2 \tag{4}$$

At the same time, expression is the rock mass strain energy:

$$V_\varepsilon = \frac{p^2 h^3}{6EI} \tag{5}$$

$$E = \lambda V_\varepsilon \tag{6}$$

Thus, further expressions of seismic energy and magnitude (17) can be obtained:

$$\lg[\lambda \frac{(C + \sigma_n \tan\phi)^2 \cdot h^5 \cdot l^2}{6EI}] = 1.5M + 11.8 \tag{7}$$

Transform the equation into:

$$\lg(\frac{\lambda h^5 l^2}{6EI} \sigma_n{}^2 + \frac{\lambda C h^5 l^2 \tan\phi}{3EI} \sigma_n + \frac{\lambda C^2 h^5 l^2}{6EI}) = 1.5M + 11.8 \tag{8}$$

And,

$\frac{\lambda h^5 l^2}{6EI} = \xi_1$. $\frac{\lambda C h^5 l^2 \tan\phi}{3EI} = \xi_2$. $\frac{\lambda C^2 h^5 l^2}{6EI}) = \xi_3$

$$(\xi_1、\xi_2、\xi_3 \neq 0 \text{ and they are positive}) \tag{9}$$

Then,

$$\lg(\xi_1 \sigma_n^2 + \xi_2 \sigma_n + \xi_3) = 1.5M + 11.8 \tag{10}$$

The expression actually gives that the earthquake magnitude depends on the ultimate stress of the rocks on both sides of the fault plane when they are broken, and the fracture space and the mass of the shaking rock mass are constant. The left-hand side of this compound function is an increasing function, and the bigger the sigma n, the bigger the M value. That is to say, the greater the ultimate strength of the rock, the greater the potential energy stored before deformation and fragmentation, and the greater the energy released by seismic waves.

The effective stress of the rock is affected by pore water pressure [12]. Thus the pressure value of water injection in the salt well and the difference between water injection and water output affect the rock strength of the structural plane, which further affects the strain energy and seismic wave radiation energy of the rock mass [13].

5. Bayesian network seismic risk assessment model

According to the statistics of earthquake frequency and magnitude in the Changning area before April 2006, the "frequency distribution balance" of earthquakes was the same. Subsequently, the overall earthquake frequency increased significantly. Therefore, taking April 2006 as the boundary, bayesian probability models of injection travel and earthquake frequency are respectively made,

Which are expected to be used to predict the likelihood of future earthquakes [14].

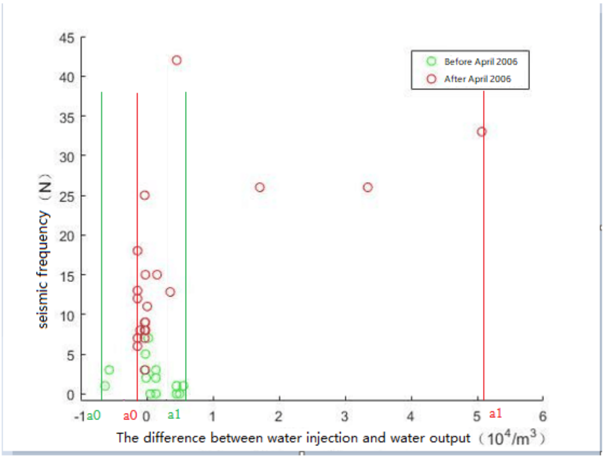

Figure. 8 Correlation curve of the difference between injection amount and output amount and seismic frequency (a_1 is the minimum value observed in the whole data set, that is, the data set after capacity differentiation; a_0 is the maximum value of the parameter.)

The corresponding lattice diagram of the relation between note - travel and earthquake frequency is made by using time as the implicit relation.

First, the bayesian probability is calculated by analyzing the data before April 2006. Basic assumptions:

(1) The difference of water injection has a major correlation with subsequent earthquakes.

(2) The probability of earthquake occurrence can be measured by the density of earthquake frequency value.

(3) A certain seismic frequency value density is taken as the threshold value for determining the seismic activity of a certain injection. Above this threshold there is a probability that seismic activity will occur. This probability is determined by the number of seismically active and non-seismically active points. The parameters that define thresholds are those that have a certain capacity to recognize, which is to ignore some scattered points.

Statistical analysis of key value and calculation of probability distribution: The parameter of water injection-output difference is a . According to existing statistics, when the parameter value is greater than a_0 and less than a_1, Changning will show seismic activity, while the parameter value is less than a_0, it does not show any seismic activity. Therefore, assume A is threshold value, when the parameter $a < A$, seismic activity will never occur, but the case of $a \geq A$ cannot be ruled out. Considering all the above factors, Bayes' theorem can be used to estimate:

$$P(A \mid data) = \frac{P(data \mid A) \cdot \pi(A)}{\int_{r}^{a_0} P(data \mid A) \cdot \pi(A) dA} \quad (11)$$

Where *P (data|)* is likelihood probability, *P (data|)* is posterior probability, and the integral range A is all possible values. π (A) Is the prior probability distribution of A, including the distribution of all prior information on A. It is known that A can be taken $[r, a_0]$ (r, less than a_0, is a constant value of the difference between injection-output amount, generally it should be taken according to the existing relevant data and less than or equal to difference between injection-output amount in the data set), so a constant probability distribution is selected:

$$\pi(A) = 1/(a_0 - r) \quad (12)$$

The probability of m (m>1) data points falling within the range is proportional to (a_1 − A)$^{-m}$, where m is all the data points in the graph[a_0, a_1].Put the value into the formula(11) and the probability distribution of A is:

$$P(A \mid data) = \frac{(m-1)(a_1 - A)^{-m}}{(a_1 - a_0)^{1-m} - (a_1 - r)^{1-m}} \tag{13}$$

When m =1, the probability distribution of A is:

$$P(A \mid data) = \frac{(a_1 - A)^{-1}}{\ln((a_1 - a_0)/(a_1 - r))} \tag{14}$$

r Is -1 based on the experimental data. According to the existing data set(a_0, a_1), let the value be (-0.1, 5.1) covering the statistical data points of the entire data set, and the statistical value of m is 19, then the probability distribution of A is:

$$P(A \mid data) = \frac{18(5.1 - A)^{-19}}{5.2^{-18} - 6.1^{-18}} \tag{15}$$

The values range from 0.177 to 3.668.

The correlation probability value is (-0.7, 0.6) after April 2006, and the statistical value m was 12. Finally, the probability distribution is:

$$P(A \mid data) = \frac{11(0.6 - A)^{-12}}{1.3^{-11} - 1.6^{-11}} \tag{16}$$

The values range from 0.780 to 9.421.

In a certain probability, bayesian probability model can be used to predict the possibility of future earthquakes and evaluate the risk of water injection in the early stage according to the relationship between the difference of injection to output amount and earthquake frequency,.The calculated results are not only related to the data distribution range but also to the concentration of points. Within a certain range of water injection difference, the more frequent earthquakes occur in each year (i.e. the more points in FIG. 8), the larger the calculation result, the more prone induced earthquakes.

6. Conclusion

Exploring the seismic mechanism induced by water injection in salt well and establishing the risk assessment model have the following significance:

(1) The expression of the relationship between magnitude and rock strength are given while discussing the relationship between water injection and earthquake in salt well. It provides practical basis for risk prediction of future salt well mining.

(2) Bayesian method is suitable for the case of small number of samples and lack of a large number of independent experiments. Thus the bayesian probability algorithm is considered to be highly reliable.

The model established in this paper is mainly aimed at the Changning region, so the following problems should be paid attention to when it is applied to other regions:

(1) Due to different geological and structural conditions in different areas, accurate parameters cannot be given, so it is necessary to modify the parameters according to the actual situation.

(2) On the fault plane, it is necessary to add appropriate parameters to modify the model in order to obtain more reasonable calculation results.

(3) Although Bayesian method is highly reliable, Bayesian hypothesis is prone to controversy.

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