

Article



Numerical Simulation of Ground Subsidence Response Conditional on Geothermal Exploitation in a Karst Reservoir Area of North China

Yahui Yao ^{1,2,3,†}, Shengtao Li ^{2,3,†}, Xiaofeng Jia ^{2,3,*}, Jian Song ^{2,3}, Dongdong Yue ^{2,3}, Qiuxia Zhang ^{2,3} and Hong Xiang ^{2,3}

- ¹ School of Resource and Earth Science, China University of Mining and Technology, Xuzhou 221116, China
- ² Center for Hydrogeology and Environmental Geology Survey, China Geological Survey, Tianjin 300304, China
- ³ Tianjin Engineering Center of Geothermal Resources Exploration and Development, Tianjin 300304, China
 - Correspondence: jiaxiaofengdaxia@163.com
- + These authors contributed equally to this work.

Abstract: Carbonate karst geothermal resources are widely distributed and have large reserves in North China. Currently, the scale of exploitation and utilization of the carbonate karst geothermal resources is gradually increasing. In this work, a geothermal exploitation area where the karst geothermal reservoirs are exploited on a large scale is selected as the study area, and methods including experiment and numerical simulation are used to study the exploitation-induced ground subsidence problems based on the long-term water level monitoring data of the geothermal reservoir. Through analyses of ground subsidence caused by water level changes in the geothermal reservoir, the following conclusions were obtained. The water level drawdown of different types of geothermal reservoirs had different effects on ground subsidence. The maximum ground subsidence of the study area caused by the water level decline of the Jxw carbonate geothermal reservoir was only 0.29 mm/a from 1983 to 2019, which is generally insignificant. In contrast, the same water level change of the Nm sandstone geothermal reservoir was predicted to cause 8.9 mm/a ground subsidence. To slow down or even prevent the ground subsidence, balanced production and reinjection are required. From the result of this work, it can be concluded that the decline of the water level of the Jxw carbonate geothermal reservoir caused by current large-scale geothermal exploitation will not cause serious ground subsidence.

Keywords: karst geothermal reservoir; large-scale exploitation; ground subsidence; numerical simulation; North China

1. Introduction

Geothermal energy is a type of clean and renewable energy with strong competitiveness. The development and utilization of geothermal energy play an important role in clean heating in winter and in haze treatment. Excessive exploitation of geothermal water can lead to a water level decline in the geothermal reservoir and ground subsidence [1,2]. Currently, reinjection is an effective measure to alleviate the decline of water level and maintain the geothermal reservoir pressure [3]. However, it is generally difficult to achieve the balance of production and reinjection due to many factors such as geological conditions and technical level.

With the increasing scale of geothermal development, more attention should be paid to the problem of ground subsidence caused by large-scale geothermal development [4–6]. Recent studies have shown that exploitation of the sandstone porous geothermal reservoir has a certain contribution to ground subsidence, but there is still a lack of quantitative research on whether the development of the carbonate geothermal reservoir causes ground



Citation: Yao, Y.; Li, S.; Jia, X.; Song, J.; Yue, D.; Zhang, Q.; Xiang, H. Numerical Simulation of Ground Subsidence Response Conditional on Geothermal Exploitation in a Karst Reservoir Area of North China. *Sustainability* **2023**, *15*, 8089. https:// doi.org/10.3390/su15108089

Academic Editors: Qiang Sun, Weiqiang Zhang and Yuliang Zhang

Received: 29 March 2023 Revised: 9 May 2023 Accepted: 11 May 2023 Published: 16 May 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). subsidence [7]. The carbonate geothermal reservoir, known as the karst geothermal reservoir due to the existence of rock karstification to varying degrees, is a typical hydrothermal geothermal resource [8] and is considered to be the most important thermal water resource outside of volcanic areas [9]. Large karst geothermal reservoirs are developed in carbonate reservoirs widely distributed in North China, with excellent geothermal resource quality, large water volume, good water quality, high temperature and easy production and reinjection [10]. It is the main area for the development and utilization of carbonate karst geothermal reservoirs in the middle of Bohai Bay Basin [11], with a cumulative heating area of more than 40 million square meters. In this work, taking a concentrated production area of a karst geothermal reservoir in North China as the study area, the objective is to evaluate the impact of karst reservoir pressure drop on ground subsidence. The study is of significance to the sustainable development of geothermal resources and environmental protection.

2. Study Area

2.1. Location

The study area is structurally located in the north-central part of the Jizhong Depression in Bohai Bay Basin (Figure 1), where the karst geothermal reservoir of the Wumishan formation of the Jixian system (Jxw) is taken as the exploitation target. There are 20 geothermal wells in the study area, including 9 producing wells and 11 reinjection wells. The distribution of geothermal wells is shown in Figure 1. The geothermal wells offer 63~78 °C hot water at about 100 m³/h flow rate. According to the statistics from 2014 to 2015, the annual production and reinjection volume of this area was 1,903,000 m³, and the heating area was 1,088,000 m², which are categorized as large-scale production and reinjection levels.



Figure 1. Location of the study area in Bohai Bay basin (North China). The distribution of geothermal wells in the study area and photographs of producing and reinjection wells.

2.2. Geological and Hydrogeological Background

The stratum lithology encountered by drilling in the study area is clay and sandy clay in the Quaternary (Q), siltstone and mudstone in the Minghuazhen formation of the

Neogene system (Nm) and dolomite in the Wumishan formation of Jixian system (Jxw) in Middle-upper Proterozoic. The geothermal reservoirs in the area include the sandstone geothermal reservoir of Nm and the karst fissure geothermal reservoir of Jxw, among which the exploitation of the Nm reservoir is restricted by the government due to environmental protection. In the study area, the caprock is composed of the Q and Nm strata, which have good thermal insulation, and it is therefore an ideal regional caprock. The Nm is not only a geothermal reservoir but also a caprock of the underlying Jxw. Hot water in the karst reservoirs may be supplied by the lateral recharge and ascending deep fluids through transmissible pores and fractures or faults [12–14]. According to the previous observation data of geothermal wells in the study area, the temperature, quantity and quality of the hot water are relatively stable, but the water level shows a downward trend year by year. The groundwater in the hydrothermal systems of the study area is mostly derived from meteoric sources. Such water gradually infiltrates into the ground and is then driven by topographic relief or gravity force to move through the deep strata. Groundwater in the deep aquifers is then heated by surrounding hot rocks [15]. The geothermal genesis model of the large-scale karst geothermal system is developed into a low-temperature convection–conduction geothermal system in a sedimentary basin [10].

3. Material and Methods

3.1. Coupling Software and Mathematical Model

COMSOL is a large and advanced numerical simulation software, which is widely used in scientific research and engineering calculation in various fields and can simulate various physical processes [16–18]. This study used the Poroelasticity multiphysics node of COMSOL, which includes the time rate of change in strain from the Solid Mechanics interface in the Darcy's Law interface and adds the fluid pressure gradient as stress contribution in the Solid Mechanics interface. The following sections describe the built-in equations when using the Poroelastic Material feature.

(1) Fluid flow

Use the Darcy's Law interface to estimate the flow field in the poroelastic model with the pressure head formulation

$$\rho_f S_\alpha \frac{\partial H}{\partial t} + \nabla \cdot \rho_f [-K \nabla H] = -\rho_f \alpha_B \frac{\partial}{\partial t} \varepsilon_{vol} \tag{1}$$

where ρ_f is the fluid density, *H* is the pressure head, *K* is the hydraulic conductivity, ε_{vol} is the volumetric strain of the porous matrix, α_B is the Biot coefficient and S_{α} is Poroelastic storage coefficient.

(2) Porous matrix deformation

The governing equation for the poroelastic material model is

$$-\nabla \cdot \sigma = \rho g \tag{2}$$

where σ is the stress tensor, ρ is the total density and g is acceleration of gravity. The poroelastic material model uses Equation (2) to describe changes in the stress tensor σ and porous matrix displacement u due to boundary conditions and changes in pore pressure.

3.2. 3D Geological Model

The strata data exposed by the 20 geothermal wells in the study area are shown in Table 1, whose formations are Q, Nm and Jxw. The stratum structure is simple, and the fault structure is not developed. Among the wells, the maximum vertical thickness of Jxw exposed by well P8 is 762.5 m. Considering that the stratum thickness of Jxw is about 1400~1500 m in the study area, and the maximum drilling depth of the 20 geothermal wells is 1717.54 m, it is speculated that the stratum at the 2000 m depth of the study area is Jxw. In view of the accuracy of the 3D geological model and the efficiency of later numerical

calculations, the strata at a depth of 2000 m were selected as the bottom boundary to establish the 3D geological model. According to the stratum information of 20 geothermal wells in the study area, the depth and thickness data of each layer were obtained through interpolation (as shown in Figure 2). The 3D geological model was established according to the stratum structure from the ground surface to 2000 m below (Figure 3), whose horizontal boundary was determined according to the scope of the study area. The model was divided into 49,138 free tetrahedral mesh cells that are sufficient for calculation. On the premise of reflecting the original geological conditions as much as possible, some assumptions and simplifications were adopted for the model geological conditions. Specifically, only the gravity was considered for the original stress field, and each rock or soil layer was treated as a uniform continuous medium. For the Jxw geothermal reservoir, according to the logging interpretation results and reservoir characteristic parameters of the P4 well (Table 2), its fracture development section and dense section are distributed alternatively, and the reservoir thickness ratio is 32.62%. Considering the large differences in physical and mechanical properties between the fracture development section and the dense section of the Jxw geothermal reservoir and the difficulties of establishing a geological model consistent with the real reservoir due to the complex development and distribution of fractures in the Jxw geothermal reservoir, the 3D geological model of Jxw exposed at a shallow depth of 2000 m was simplified into two parts, which are the karst fracture development section (Jxw-1) and dense section (Jxw-2) according to the reservoir thickness ratio parameter.

Well Type	Well	Well	Bottom Bour	ndary Depth of	f Stratum (m)	Exposed Stratum Thickness (m)		
	Number	Depth (m)	Q	Nm	Jxw	Q	Nm	Jxw
	P1	1580	364.52	850	1580	364.52	485.48	730
	P2	1301	390.3	990	1301	390.3	599.7	311
	P3	1286	312.5	1042	1286	312.5	729.5	244
Due des sins a	P4	1600	402	1070	1600	402	668	530
Producing	P5	1506.4	405	1072	1506.4	405	667	434.4
wen	P6	1250	397.7	1065	1250	397.7	667.3	185
	P7	1506	305.3	930.43	1506	305.3	625.13	575.57
	P8	1693.5	322	931	1693.5	322	609	762.5
	P9	1500	405	1052	1500	405	647	448
	R1	1068.93	332.5	932.3	1068.93	332.5	599.8	136.63
	R2	1500	299.9	990.35	1500	299.9	690.45	509.65
	R3	1028	400	999	1028	400	599	29
	R4	1070	390.5	1011	1070	390.5	620.5	59
Detailed	R5	1201.8	392	1030	1201.8	392	638	171.8
Keinjection	R6	1284.57	398.5	1085	1284.57	398.5	686.5	199.57
wen	R7	1501.01	398	1043.2	1501.01	398	645.2	457.81
	R8	1500	419.44	992.11	1500	419.44	572.67	507.89
	R9	1506	318.5	948.05	1506	318.5	629.55	557.95
	R10	1500	425.25	980.26	1500	425.25	555.01	519.74
	R11	1717.54	403.69	1268.3	1717.54	403.69	864.61	449.24

Table 1. List of strata data exposed by 20 geothermal wells in the study area.

Table 2. Characteristic parameters of the Jxw geothermal reservoir of P4 well in the study area.

Geothermal Well	Exposed Thickness (m)	Reservoir Thickness Ratio (%)	Crack Rate (%)	Permeability (mD)	Water Flow Rate (m ³ /h)	Water Flow Rate per Unit Thickness (m ³ /(h·m))	Water Temperature (°C)
P4 well	172.89	32.62	4.89	2.2	135.6	20.67	65







Figure 3. 3D geological model of the study area.

3.3. Setting of Boundary Conditions and Initial Conditions

The hydrogeological boundary conditions of the 3D model are described as follows. The horizontal direction of the model is considered as an infinite recharge boundary. The Jxw geothermal reservoir is in direct contact with the Nm vertically, and the thick mudstone at the bottom of the Nm, which plays a role in blocking water, directly covers the Jxw geothermal reservoir. Therefore, the upper surface of the Jxw is treated as a water barrier boundary. There is no water blocking boundary in the lower part of the Jxw, so the bottom boundary is an infinite recharge boundary. The mechanical boundary conditions of the 3D model are described as follows. The lateral sides of the model are restrained in the horizontal direction. The bottom boundary is restrained in both vertical and horizontal directions, and the top of the model is a free boundary.

The deformation calculation initiates at the initial water level, and it is assumed that the vertical displacement of all points at this time is 0. A positive deformation value indicates subsidence, and a negative deformation value indicates uplift.

3.4. Experiment and Model Parameter Acquisition

The rock mechanical parameters of the Jxw geothermal reservoir were confirmed by the triaxial compression test. The rock samples of Jxw were taken from the outcrop in the mountain area near the study area. The RMT-150C rock mechanics measuring system was applied in the Institute of Rock and Soil mechanics, Chinese Academy of Sciences. From the triaxial compression test results (Table 3) and the stress–strain curves (Figure 4), the triaxial compressive strength and elastic modulus of the rock samples basically increase with the increase in confining pressure. The triaxial compressive strength of rock samples ranges from 341.753 to 507.428 MPa, and the elastic modulus ranges from 46.951 to 52.793 GPa. The main physical and mechanical parameters for each stratum of the 3D model are shown in Table 4. Due to the complex fracture structure development of the carbonate geothermal

reservoir, it is difficult to obtain the Biot coefficient reflecting the real reservoir through the experimental test. The Biot coefficients of Jxw-1 and Nm were referred to in [19]. The elasticity modulus of Jxw-2 was determined using the above test results. The elasticity modulus of Jxw-1 was referred to in [20]. The elasticity moduli of Q and Nm were referred to in [21].

Table 3. Triaxial compression test results of the Jxw geothermal reservoir.

Rock Mechanical Parameters	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Confining pressure (MPa)	5.0	10.0	15.0	2.481	7.501	20
Compressive strength (MPa)	342.615	380.962	412.960	341.753	428.439	507.428
Elastic modulus (GPa)	49.784	46.951	51.137	47.111	52.793	53.837



Figure 4. Stress-strain curve of triaxial compression test of the Jxw geothermal reservoir.

Table 4. Physical and mechanical parameters for each stratum of the 3D geological model.

Stratum	Density (kg/m ³)	Elastic Modulus (MPa)	Poisson's Ratio	Biot Coefficient	Porosity	Permeability (mD)
Q	2000	500	0.35	_	_	_
Nm	2300	1500	0.3	0.8	0.1	1
Jxw-1	2600	20,000	0.27	0.6	0.05	2.2
Jxw-2	2800	50,000	0.25		—	—

4. Results and Discussion

Firstly, this study simulated the ground subsidence response under the condition of large-scale development of the Jxw karst geothermal reservoir from 1983 to 2020, based on the long-term water level monitoring data of the X101 and D02 well before heating season in November every year. The X101 well, a water-level observation station of the Jxw reservoir located about 2 km to the south of the study area, recorded the water level data in 1983 and the period from 2000 to 2014. The D02 well, another water-level observation station of the Jxw reservoir for the Jxw reservoir located about 8 km to the north of the study area, continuously recorded

the water level data from 2019 to 2020. The long-term water level monitoring data are shown in Figure 5. It should be noted that the local government banned a number of illegal geothermal wells and strengthened the management measures of balanced geothermal production and reinjection from 2019, causing the water level in the same period in 2020 to be higher than that in 2019. The exploitation of the Nm geothermal reservoir in the study area has been forbidden. However, in order to compare and study the impact of water level drop of the Nm semi-consolidated sandstone geothermal reservoir on ground subsidence, the simulations considering different water level drawdown scenarios were also carried out for the Nm reservoir. The water level monitoring data of the Jxw reservoir were also adopted in the simulation of the Nm reservoir. The simulation results of maximum surface deformation caused by different water level drawdown of the Jxw and Nm geothermal reservoirs are shown in Table 5 and Figure 6.



Figure 5. Simulation results of maximum ground subsidence corresponding to the water level of the Jxw and Nm geothermal reservoirs in different years.

Table 5. Statistics of simulation results of maximum surface deformation caused by different water level drawdown of the Jxw and Nm geothermal reservoirs.

Number	Year	Year Water Level (m)	Drawdown (m)	Maximum Ground Subsidence Caused by Water Level Drop (mm)		Annual Average Value of Maximum Ground Subsidence Caused by Water Level Drop (mm/a)	
				Jxw	Nm	Jxw	Nm
1	1983	-0.75	0	0	0		
2	2000	-35.8	35.05	3.2	96.8	0.12	3.6 (2000–2006)
3	2001	-38.6	37.85	3.4	104.5		
4	2002	-39.6	38.85	3.5	107.3		
5	2003	-41.4	40.65	3.7	112.2		
6	2004	-41.4	40.65	3.7	112.2	(2000–2006)	
7	2005	-42.2	41.45	3.8	114.4		
8	2006	-43.7	42.95	3.9	118.3		
9	2007	-53.3	52.55	4.7	145.2		
10	2008	-58.9	58.15	5.3	160.6	0.6 (2006–2010)	18.4
11	2009	-66.5	65.75	5.9	181.5		(2006–2010)
12	2010	-70.4	69.65	6.3	191.9		

Number	Year	Water Level (m)	Drawdown (m)	Maximum Ground Subsidence Caused by Water Level Drop (mm)		Annual Average Value of Maximum Ground Subsidence Caused by Water Level Drop (mm/a)	
				Jxw	Nm	Jxw	Nm
13	2011	-72.7	71.95	6.5	198.5	0.52	16.1 (2010–2013)
14	2012	-77.3	76.55	6.9	211.1	(2010, 2012)	
15	2013	-87.9	87.15	7.9	240.3	(2010–2013)	
16	2019	-117.0	116.25	10.5	320.5	-0.3	-8.3
17	2020	-114.0	113.25	10.2	312.2	(2019–2020)	(2019-2020)

Table 5. Cont.

Note: Taking the water level in 1983 as the initial state, it is assumed that the vertical displacement in this state is 0.



Figure 6. Distribution of deformation caused by water level falling from -0.75 m to different depths of Jxw. (a) The water level dropped to -35.8 m (2000 year), (b) The water level dropped to -70.4 m (2010 year), (c) The water level dropped to -87.9 m (2013 year), (d) The water level dropped to -117 m (2019 year).

4.1. Jxw Geothermal Reservoir

According to the simulation results (Table 5, Figures 5 and 6), the water level drawdown of the Jxw geothermal reservoir has little effect on the ground subsidence. From 1983 to 2019, the water level decreased from -0.75 m to -117 m, with the water level decline rate reaching 3.23 m/a, which only caused maximum ground subsidence of 10.5 mm and average annual ground subsidence of 0.29 mm/a. Particularly, from 2000 to 2019, due to the increase in geothermal exploitation, the water level decreased from -35.8 m to -117 m, and the water level decline rate reached 4.27 m/a. The maximum ground subsidence caused in the period was 7.3 mm, with average annual ground subsidence of 0.38 mm/a. In this work, we divided this period into the following five stages:

From 2000 to 2006 was the stage of slow increase in geothermal production; the water level decreased from -35.8 m to -43.7 m, and the water level decline rate was 1.3 m/a. The caused maximum ground subsidence was 0.7 mm, and the average annual ground subsidence was 0.12 mm/a. The period from 2006 to 2010 saw a rapid increase in geothermal production, when the water level decreased from -43.7 m to -70.4 m (6.7 m/a) and caused 2.4 mm maximum ground subsidence (0.6 mm/a). From 2010 to 2013, due to the start of the reinjection project, the decline rate of the water level slowed down. The water level dropped from -70.4 m to -87.9 m, and the water level drop rate was reduced to 5.8 m/a. The total ground subsidence caused in these 3 years was 1.6 mm (0.53 mm/a). From 2014 to 2019, the water level still showed a downward trend. However, due to the lack of monitoring data from 2014 to 2018, we only analyzed the data of 2019 here. In the year 2019, the water level dropped to -117 m, and the total land subsidence was 10.5 mm. Subsequently, 2019 to 2020 was the last stage, during which a large number of geothermal wells around the study area were shut down, causing the water level to rise from -117 m to -114 m and the land subsidence to rebound by 0.3 mm.

The above data conclude that the subsidence caused by the water level drop of the carbonate geothermal reservoir of Jxw is generally insignificant. Because the carbonate geothermal reservoir results from elastic deformation, the rebound deformation occurs when the water level rises. If the production and reinjection are balanced and the water level remains unchanged, the ground subsidence is not likely to increase. The karst fracture development section of Jxw-1 in the upper part of Jxw is the main thermal water exploitation section. The effective stress change caused by the change of water level mainly acts on the Jxw-1 section, resulting in the deformation of geothermal reservoir structure.

4.2. Nm Geothermal Reservoir

According to the simulation results (Table 5, Figures 5 and 7), with the annual increase in water level drawdown of Nm, the ground subsidence was observed. From 1983 to 2019, the water level decreased from -0.75 m to -117 m, resulting in a maximum ground subsidence of 320.5 mm and an average annual subsidence of 8.9 mm/a. From 2000 to 2019, the geothermal production increased sharply, and the water level decreased from -35.2 m to -117 m. The maximum ground subsidence caused was 223.7 mm, and the average annual ground subsidence was 11.78 mm/a. Because the Nm sandstone geothermal reservoir is a semi-consolidated formation, the effective stress change caused by the change of water level has a large deformation on the geothermal reservoir structure.

According to [22], the average annual ground subsidence caused by the development of the Nm geothermal reservoir was 8.52 mm/a in Tanggu District, Tianjin City, which is close to the simulation results of the study and can explain the rationality of the simulation results.



Figure 7. Distribution of deformation caused by water level falling from -0.75 m to different depths of Nm. (a) The water level dropped to -35.8 m (2000 year), (b) The water level dropped to -70.4 m (2010 year), (c) The water level dropped to -87.9 m (2013 year), (d) The water level dropped to -117 m (2019 year).

4.3. Analysis

From the simulation results, the water level drawdown of the Jxw carbonate reservoir and Nm sandstone reservoir showed an obvious linear correlation with the maximum ground subsidence. With the increase in water level drawdown, the ground subsidence also increases. For a given water level drop, the maximum ground subsidence caused by the Nm sandstone geothermal reservoir is nearly 30 times that of the Jxw carbonate reservoir, indicating that ground subsidence is much more sensitive to the water level change of the Nm sandstone geothermal reservoir than that of the Jxw carbonate geothermal reservoir. The main reason for this phenomenon is the difference of rock consolidation characteristics and mechanical properties between the two types of geothermal reservoirs. The Jxw carbonate geothermal reservoir is fully consolidated rock with stable mechanical properties. In contrast, the semi-consolidated rock stratum of the Nm sandstone reservoir has poor mechanical properties. The change of fluid pressure will increase the effective stress of the reservoir. The pressure increment of the reservoir structure caused by the same water level change is consistent, but the difference of ground subsidence caused is huge due to the difference of key influencing parameters such as elastic modulus and Biot coefficient.

5. Conclusions

The ground subsidence of the study area was mainly caused by the exploitation of geothermal resources and groundwater. The ground subsidence caused by groundwater exploitation in the Quaternary strata has been widely recognized. There are few studies

focusing on ground subsidence caused by geothermal reservoir exploitation. By comparing and analyzing the response relationship between ground subsidence and the water level change of geothermal reservoir in the study area, the following conclusions were obtained.

The water level drawdown of different types of geothermal reservoirs had different effects on the ground subsidence. From 1983 to 2019, the ground subsidence caused by the water level decline of the Jxw carbonate geothermal reservoir in the study area was only 0.29 mm/a, which is insignificant. In contrast, the same water level drop of the Nm sandstone geothermal reservoir was predicted to cause 8.9 mm/a ground subsidence. Under the condition of balanced production and reinjection, controlling the water level decline rate of the geothermal reservoir can effectively slow down and even prevent ground subsidence. Due to the control of internal factors such as mechanical properties and structural characteristics of the geothermal reservoir, the ground subsidence caused by the Jxw carbonate geothermal reservoir with good consolidation and strong deformation resistance is much less than that of the semi-consolidated Nm sandstone geothermal reservoir in the study area is not sensitive to water level decline. Under the current large-scale geothermal exploitation conditions, the water level decline of the Jxw carbonate geothermal reservoir will not cause serious ground subsidence.

Based on the research, we suggest that: ① Geothermal resources' exploitable volume needs to be controlled, and overexploitation is not allowed. ② Geothermal resources' exploitable volume should be determined according to the reinjection capacity of the geothermal reservoir to achieve the balance between production and reinjection. ③ Dynamic monitoring of the water levels of geothermal reservoirs should be carried out. If there is a significant decrease in water level, the geothermal development should be controlled.

Author Contributions: Conceptualization, Y.Y., S.L. and X.J.; methodology, Y.Y., S.L. and X.J.; software, Y.Y.; validation, J.S. and D.Y.; investigation, J.S., D.Y., Q.Z. and H.X.; writing—original draft preparation, X.J.; writing—review and editing, Y.Y. and S.L.; visualization, Q.Z.; funding acquisition, S.L. and X.J. All authors have read and agreed to the published version of the manuscript.

Funding: Supported by the project of China Geological Survey (No. DD20221680, No. DD20190127) and the National Key Research and Development Program (No. 2018YFC0604305).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data provided in this study can be obtained from the correspondent. Due to the privacy of this paper and other reasons, these data are not public.

Acknowledgments: The authors wish to thank the editors and reviewers for their constructive comments.

Conflicts of Interest: The authors declare that they have no potential conflicts of interest with respect to the research, authorship, and publication of this article.

References

- Liu, F.; Fu, P.; Mellors, R.J.; Plummer, M.A.; Ali, S.T.; Reinisch, E.C.; Liu, Q.; Feigl, K.L. Inferring geothermal reservoir processes at the Raft River geothermal field, Idaho, USA, through modeling InSAR-measured surface deformation. *J. Geophys. Res. Solid Earth* 2018, 123, 3645–3666. [CrossRef]
- Parks, M.; Sigmundsson, F.; Sigurðsson, Ó.; Hooper, A.; Hreinsdóttir, S.; Ófeigsson, B.; Michalczewska, K. Deformation due to geothermal exploitation at Reykjanes, Iceland. J. Volcanol. Geoth. Res. 2018, 391, 106438. [CrossRef]
- Duan, Z.; Pang, Z.; Wang, X. Sustainability evaluation of limestone geothermal reservoirs with extended production histories in Beijing and Tianjin, China. *Geothermics* 2011, 40, 125–135. [CrossRef]
- Zhang, Y.; Xiang, W.; Liu, G.; Wang, X.; Zhang, R.; Zhang, X.; Tong, J.; Yuan, H.; Zhang, C. Geodetic imaging of ground deformation and reservoir parameters at the Yangbajing Geothermal Field, Tibet, China. *Geophys. J. Int.* 2023, 234, 379–394. [CrossRef]
- Li, Q.; Han, Y.; Liu, X.; Ansari, U.; Cheng, Y.; Yan, C. Hydrate as a by-product in CO₂ leakage during the long-term sub-seabed sequestration and its role in preventing further leakage. *Environ. Sci. Pollut. R.* 2022, 29, 77737–77754. [CrossRef] [PubMed]

- 6. Li, Q.; Wu, J. Factors affecting the lower limit of the safe mud weight window for drilling operation in hydrate-bearing sediments in the Northern South China Sea. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2022**, *8*, 82. [CrossRef]
- 7. Ma, F.; Wang, G.; Zhang, W.; Zhu, X.; Zhang, H.; Sun, Z. Study on the influence mechanism of the ancient buried hill geothermal exploitation on land subsidence. *Geol. China* **2021**, *48*, 40–51.
- 8. Montanari, D.; Minissale, A.; Doveri, M.; Gola, G.; Trumpy, E.; Santilano, A.; Manzella, A. Geothermal resources within carbonate reservoirs in western Sicily (Italy): A review. *Earth-Sci. Rev.* **2017**, *169*, 180–201. [CrossRef]
- Goldscheider, N.; Mádl-Szőnyi, J.; Erőss, A.; Schill, E. Review: Thermal water resources in carbonate rock aquifers. *Hydrogeol. J.* 2010, 18, 1303–1318. [CrossRef]
- Pang, Z.; Kong, Y.; Pang, J.; Hu, S.; Wang, J. Geothermal resources and development in Xiongan New Area. Bull. Chin. Acad. Sci. 2017, 32, 1224–1230.
- 11. Wang, G.; Lin, W. Main hydro-geothermal systems and their genetic models in China. Acta Geol. Sin. 2020, 94, 1923–1937.
- 12. Kong, Y.; Pang, Z.; Pang, J.; Wang, Y.; Yang, F. Stable isotopes of deep groundwater in the Xiongxian geothermal field. *Procedia Earth Planet. Sci.* **2017**, *17*, 512–515. [CrossRef]
- 13. Kong, Y.; Pang, Z.; Pang, J.; Li, J.; Lyu, M.; Pan, S. Fault-affected fluid circulation revealed by hydrochemistry and isotopes in a large-scale utilized geothermal reservoir. *Geofluids* **2020**, 2020, 2604025. [CrossRef]
- 14. Yao, Y.; Jia, X.; Li, S.; Zhang, J.; Song, J.; Yang, T.; Yue, D. Heat flow determination of Archean strata under the karst thermal reservoir of D01 well in Xiong'an New Area. *Geol. China* **2022**, *49*, 1723–1731.
- 15. Kong, Y.; Pang, Z.; Shao, H.; Hu, S.; Kolditz, O. Recent studies on hydrothermal systems in China: A review. *Geotherm. Energy* **2014**, *2*, 19. [CrossRef]
- 16. Yue, G.; Wang, G.; Ma, F.; Zhang, W.; Yang, Z. The thermal state and geothermal energy accumulation mechanism in the Xiong'an New Area, China. *Energ. Exploit.* 2019, *37*, 1039–1052.
- 17. Wang, Z.; Zhang, C.; Jiang, G.; Wang, Y.; Hu, S. Effect of different exploitation schemes on production performance from the carbonate reservoir: A case study in Xiong'an new area. *J. Clean. Prod.* **2021**, *314*, 128050. [CrossRef]
- 18. Liu, H.; Wang, H.; Lei, H.; Zhang, L.; Bai, M.; Zhou, L. Numerical modeling of thermal breakthrough induced by geothermal production in fractured granite. *J. Rock Mech. Geotech. Eng.* **2020**, *12*, 900–916. [CrossRef]
- 19. Bai, L. Experimental Analysis of Rock Biot Coefficient and Engineering Application of Geological Disposal of Carbon Dioxide. Master's Thesis, Jilin University, Changchun, China, 2016.
- Li, Y.; Zhang, B.; Xing, Y.; Wang, G. Fragmentation law of carbonate rocks under different confining pressure in Gaoyuzhuang Formation, Gaoyang geothermal field, Xiong'an New Area. *Geol. China.* 2021. Available online: https://kns.cnki.net/kcms/ detail/11.1167.P.20210419.1328.006.html (accessed on 19 April 2021).
- 21. Ma, S.; Wang, X.; Ma, X.; Cao, X. Experimental study on mechanical characters of Neogene weak cementation rock. *Yellow River* **2016**, *38*, 121–124.
- Li, H.; Xiao, G.; Yang, J.; Zhao, C.; Xiao, Y. Precise identification of land-subsiding layers and reconstruction of subsidence process in Tianjin Binhai New Area. *Geol. Bull. China* 2016, 35, 1646–1652.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.