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Calculation of storage capacity of geothermal resources by weighted element weight method — A case study of Zhangjiapo Formation in Xi'an Depression*

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ABSTRACT

Weighted element method is proposed in this paper to improve the accuracy of calculating storage capacity of geothermal reservoirs. This method makes full use of all geothermal wells in the calculation region, which is defined by every three neighboring geothermal wells. The calculation region is divided into many calculation elements. As a result, the entire calculation region of the distribution parameters is discretized into independent in each element with lumped parameters. The arithmetic mean of three-node parameters in each element is used as the lumped parameter, and the block with the same set of parameters is divided into calculation regions as small as possible. The effect of one element as well as its parameters in the entire calculation region depends on the weight of the area of this element in the whole calculation area. The weighted element method can be used to calculate the volumetric water storage capacity of geothermal fluids, elastic release storage capacity, geothermal storage capacity of volume water, geothermal energy storage capacity of elastic releasing water, geothermal storage capacity of geothermal reservoir rocks for each element, respectively. The storage capacities of various elements and the entire calculation regions can be calculated with superposition. The proposed approach was used to calculate the storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression, in which data of 28 existing geothermal wells were available. If the geothermal energy recovery is set at 10% and theexploitation remains stable, the geothermal energy contained in the geothermal reservoir can be extracted for more than 7,000 years. Under the current conditions of exploitation technology, the actual geothermal energy that can be effectively exploited and used is 3301.419×10^8 kcal, which is equivalent to standard coal of 47.1631×10^4 t.

Keywords: Weighted element method; Geothermal resources; Storage capacity; Zhangjiapo Formation; Xi'an Depression

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1. Introduction

Calculation of storage capacity of geothermal resources is discussed in this study. From the perspective of geothermal resources the storage capacity has to include two aspects, i.e. storage capacity of geothermal fluid and geothermal reservoir. The geothermal storage capacity of geothermal reservoir also contains two aspects, i.e. rock geothermal storage capacity of geothermal reservoir and geothermal fluid storage capacity, including storage capacity of volume water and that of elastic releasing water. Therefore, the storage capacity of geothermal resources should be calculated based on the calculation of (1) volumetric water storage capacity of geothermal fluid, (2) elastic release storage capacity of geothermal fluid, (3) geothermal storage capacity of geothermal fluid and (4) rock geothermal storage capacity of geothermal reservoir.

Storage capacity, that is "static reserve" in the traditional concepts, does not involve any forms of "recharge". Under the natural conditions, it does not change with the year or even the season. The storage capacity depends on geological parameters of the geothermal reservoir. However, geothermal geological parameters in different blocks and different strata are heterogeneous, that is, parameters are distributed and vary with spatial locations. Therefore, the calculation on storage capacity of geothermal resources should fully reflect the corresponding relationship between geothermal geological parameters and the spatial distribution of geothermal reservoir.

Conventionally, the calculation region is divided into a number of "lumped parameter" regions when the distribution parameters method is used. Each parameter is averaged over each block as the "lumped parameter". The approach is effective, but distortions or errors exist. The smaller the blocks are, the smaller the distortions or errors would be.

Reduction in the error through finer division of blocks requires in-depth exploration. In the framework of finite-element method in numerical analysis, the "weighted element method" is proposed for the calculation of storage capacity of geothermal resources. The weighted element method is introduced in the first part of this paper, and then in the second part, the method is applied to the calculation of storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression.

2. Formula and parameters for the calculation of storage capacity of geothermal resources

For the calculation of the four storage capacities of geothermal resources, the formulae used in the calculation are introduced below.

2.1. Calculation formula of storage capacity of geothermal water

According to the provisions of GB 50027-2001 "9.3. Calculation of storage capacity", the elastic storage capacity of a confined aquifer can be calculated with the formula as follows:

$$W = F\mu^{*}h \tag{1}$$

where W indicates the elastic storage capacity of groundwater (m^3); F indicates the aquifer area (m^2); μ^* indicates the elastic release coefficient; and h indicates the height of piezometric pressure of the aquifer above the roof (m) .

It is also provided in GB 50027-2001 "9.3. Calculation of storage capacity" that storage capacity of phreatic aquifer can be calculated with the formula as follows:

$$W = \mu V \tag{2}$$

where W indicates the groundwater storage capacity (m^3); μ indicates the aquifer specific yield; and V indicates the aquifer volume (m^3).

2.2. Calculation formula of geothermal storage capacity

The geothermal energy of geothermal reservoirs is stored in geothermal fluids between the geothermal reservoir medium (sandstone) and the geothermal reservoir fluid. The total amount of geothermal energy stored in geothermal reservoir Q_R (10^3 kcal) is the sum of these two parts, namely the total amount of geothermal energy in the geothermal reservoir medium (sandstone) Q_{RockR} (10^3 kcal) and that in the geothermal fluid Q_{WaterR} (10^3 kcal). The calculation formula of geothermal energy is adopted as follows:

$$Q_R = Q_{RockR} + Q_{WaterR} \tag{3}$$

where

$$Q_{RockR} = FM(1-\mu)p_{Rock}C_{Rock}(t-t_o)$$

$$Q_{WaterR} = Q_{Water\,volume\,R} + Q_{Water\,elasticity\,R}$$

The total geothermal energy of volume storage capacity of geothermal water is

$$Q_{Water\,volume\,R} = FM\mu o_{water}C_{water}\left(t-t_0\right)\left(10^3\ \text{kcal}\right)$$

And the total geothermal energy in elastic storage capacity of geothermal water is

$$Q_{water\,elasticity\,R} = F\,h\,\mu^{*}\,p_{water}C_{water}\left(t-t_0\right)\left(10^3\ \text{kcal}\right)$$

where M indicates the thickness of the geothermal reservoir medium (sandstone) (m); p_{Rock} indicates the density of the geothermal reservoir medium (sandstone) (t/m^3); pwater indicates the water density, which varies with temperatures (t/m^3); C_{Rock} indicates the specific heat of geothermal reservoir medium (sandstone) [10^3 kcal/(t·°C)]; Cwater indicates the specific heat of water, which varies with temperatures [10^3 kcal/(t·°C)]; t indicates the vertical average temperature of geothermal reservoir (°C); and t_0 indicates the basic temperature (°C), and $t_0 = 25$°C.

2.3. Parameters involved in the calculations of storage capacity of geothermal energy

Eqs. (1)–(3) calculate the storage capacity of geothermal energy. There are 11 parameters involved as follows:

1) Thickness of the sandstone consisting of the geothermal reservoir (m)
2) Buried depth of roof of the geothermal reservoir (m)
3) Porosity of the sandstone consisting of geothermal reservoir (%)
4) Elastic drainable porosity in the geothermal reservoir
5) Rock density of the sandstone consisting of the geothermal reservoir (t/m^3)
6) Rock specific heat of the sandstone of the geothermal reservoir [10^3 kcal/(t·°C)]
7) Vertical average temperature of the geothermal reservoir (°C)
8) Initial water level value above the surface of geothermal reservoir (m)
9) Water density of the geothermal reservoir (t /m^3)
10) Water specific heat of the geothermal reservoir [10^3 kcal/(t·°C)]
11) The calculated basic temperature (°C)

3. Introduction to weighted element method

The weighted element method is proposed to improve the calculation accuracy of geothermal resource storage capacity of geothermal reservoirs. The weighted element method attempts to divide the blocks with the same set of parameters into calculation regions as small as possible. The idea is to fully utilize all geothermal wells with geothermal parameters. Specifically, every three adjacent geothermal wells are divided into various calculation blocks, each of which is regarded as a calculation "element". Each calculation element is calculated separately. Three points not in a straight line determine a plane. Because the triangle, as the plane figure formed by three points, is the simplest plane figure, the triangle is called the "simplex". Viewed from the element meshing, the three geothermal wells with the same set of parameters are meshed into the smallest elements as various triangles, because fewer than three points would not determine a plane.

Among these triangle elements, the effect of each element and its parameters in the whole calculation region depends on the weight of area of the element in the whole calculation area. The greater area of the element, the greater weight of the element and its parameters in the entire calculation region, and the stronger effects would be. Accordingly, this method is named as the " weighted element method".

The "weighted element method" is essentially to achieve discretization through element meshing. The whole calculation region with distributed parameters is discretized into various independent regions with lumped parameter as the calculation elements. The arithmetic mean of its three node parameters of each element is set as the lumped parameter of the region (i.e. the element). Because the "simplex" triangular element is the smallest element in the division, the distortion of parameters is minimized. Therefore, this method is more accurate than the method of averaging parameters of the block containing all geothermal wells concerned.

In order to calculate storage capacity of geothermal resources with the "weighted element method", "calculation procedure of geothermal storage capacity with weighted element method" has been prepared. In addition to the 11 parameters of each element in the calculation region, the program outputs 5 items of data of storage capacity of geothermal resources equivalent to that of standard coal.

This method can also be adopted for calculations on groundwater storage capacity of other types.

4. Determination method of parameters

The 11 parameters adopted in the calculation from Eqs. (1)–(3) are determined by the following methods in this study.

*4.1. Calculation method of elastic storage coefficient μ **

The setting of elastic storage coefficient μ^* is very important because it directly restricts the elastic release quantity. Under the current technical conditions, the quantity of exploitable geothermal resource accounts for a small proportion in the actual elastic release quantity of geothermal water. In this study, the elastic storage coefficient μ^* of geothermal reservoir was calculated using Theis formula, based on the original data of pumping test of geothermal wells. The Theis formula is shown as follows:

$$s = \frac{Q}{4\pi T} W(u) \quad u = \frac{\mu^* r^2}{4Tt} \tag{4}$$

where T indicates the transmissibility of the aquifer, $T = KM$ (m^2/d); and $W(u)$ indicates the Theis well function

$$w(u) = \int_u^\infty \frac{1}{y} e^{-y} dy$$

In the Theis formula, difficulty lies in the calculation of the Theis well function $W(u)$. The Theis well function $W(u)$ is an exponential integral which can be calculated by a number of methods such as table look-up method, iterative calculation method, and convergence series approximate representation calculation method. In this study, the iterative method was adopted, and the Fortran language was used for programming. Calculation of elastic storage coefficient μ* of the geothermal reservoirs of all geothermal wells with original pumping test data was conducted.

The Fortran language source program is applicable for unbounded confined aquifers. Pumping with constant rate was conducted in the main hole, and the observed drawdown diachronic value was $t_i - s_i$ (i = 1, 2, ..., n) at the location r away from the pumping well.

T_0 and μ^*_0 are set as the approximate values of T and μ*, respectively. The errors of them relative to the precise values of T, μ* are ΔT and Δμ*, respectively, namely $T = T_0 + \Delta T$, and $\mu^* = \mu^*_0 + \Delta\mu^*$.

Eq. (4) can be expressed in the form of exponential integral:

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{1}{y}e^{-y}dy \quad \left(u = \frac{\mu^* r^2}{4Tt}\right) \tag{5}$$

According to the Taylor formula, Eq. (5) is expanded at (T_0, μ^*_0), and only the first derivative term is taken, and then we obtain:

$$s^* = s_0(t) + \left(\frac{\partial s}{\partial T}\right) + \left(\frac{\partial s}{\partial \mu^*}\right)\Delta\mu^* \tag{6}$$

where

$$\begin{cases} \left(\dfrac{\partial s}{\partial T}\right)_0 = \dfrac{s_0(t)}{T_0} + \dfrac{Q}{4\pi T_0^2}\exp\left(\dfrac{\mu^*_0 r^2}{4T_0 t}\right) \\ \left(\dfrac{\partial s}{\partial \mu^*}\right)_0 = -\dfrac{Q}{4\pi T_0 \mu_0^*}\exp\left(-\dfrac{\mu_0^* r^2}{4T_0 t}\right) \end{cases} \tag{7}$$

$s_0(t)$ indicates the depth of precipitation of the observation hole at time moment t calculated with Eq. (1) based on $T0$ and μ^*_0. According to the least square method, ΔT and Δμ* can be determined, then T and μ* are obtained. Therefore, the objective function E (ΔT, Δμ*) can be constructed:

$$\begin{aligned} &E(\Delta T, \Delta\mu^*) \\ &= \sum_{i=1}^n (s_1 - s^*)^2 = \sum_{i=1}^n \left[(s_1 - s_0) - \left(\frac{\partial s}{\partial T}\Delta T + \frac{\partial s}{\partial \mu^*}\Delta\mu^*\right)\right]^2 \\ &= \sum_{i=1}^n (s_1 - s_0)^2 - 2\Delta T\sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial T} - 2\Delta\mu^*\sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial \mu^*} \\ &+ \sum_{i=1}^n \left[\left(\frac{\partial s}{\partial T}\right)^2 (\Delta T)^2 + \left(\frac{\partial s}{\partial \mu^*}\right)^2 + 2\frac{\partial s}{\partial T}\frac{\partial s}{\partial \mu^*}\Delta T\Delta\mu^*\right] \end{aligned}$$

In order to minimize $E(\Delta T, \Delta\mu^*)$, $\partial E/\partial\Delta T = 0$, $\partial E/\partial\Delta\mu^* = 0$, and then:

$$\begin{cases} \displaystyle\sum_{i=1}^n \left(\frac{\partial s}{\partial T}\right)^2 \Delta T + \sum_{i=1}^n \left(\frac{\partial s}{\partial T}\frac{\partial s}{\partial \mu^*}\Delta\mu^*\right) = \sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial T} \\ \displaystyle\sum_{i=}^n \left(\frac{\partial s}{\partial T}\frac{\partial s}{\partial \mu^*}\right)\Delta T + \sum_{i=1}^n \left(\frac{\partial s}{\partial \mu^*}\right)^2 \Delta\mu^* = \sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial \mu^*} \end{cases} \tag{8}$$

By solving Eq. (8) the following can be obtained:

$$\begin{cases} \Delta\mu^* = \dfrac{\displaystyle\sum_{i=1}^n \left(\frac{\partial s}{\partial T}\right)^2 \sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial \mu^*} - \sum_{i=1}^n \left(\frac{\partial s}{\partial T}\frac{\partial s}{\partial \mu^*}\right)\sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial T}}{\displaystyle\sum_{i=1}^n \left(\frac{\partial s}{\partial T}\right)^2 \sum_{i=1}^n \left(\frac{\partial s}{\partial \mu^*}\right)^2 - \left[\sum_{i=1}^n \left(\frac{\partial s}{\partial T}\frac{\partial s}{\partial \mu^*}\right)\right]^2} \\ \Delta T = \dfrac{\displaystyle\sum_{i=1}^n (s_1 - s_0)\frac{\partial s}{\partial T} - \sum_{i=1}^n \left(\frac{\partial s}{\partial T}\frac{\partial s}{\Im \mu^*}\right)\Delta\mu^*}{\displaystyle\sum_{i=1}^n \left(\frac{\partial s}{\partial T}\right)^2} \end{cases} \tag{9}$$

Below is the actual calculation process:

1. The first given values of T_0 and μ^*_0, or the T and μ* values in last round of iterative calculation, which do not meet accuracy requirements, assigned to T_0 and μ^*_0, are substituted into Eq. (4) to calculate the s0(t) value,
2. The first derivative values of T_0 and μ^*_0 are calculated and then substituted into Eq. (9) to calculate ΔT and Δμ*. And T and μ* values in the current round of iteration are obtained.
3. Test whether the accuracy requirements are met or not. If not, the next round of iterative calculation proceeds until the accuracy requirements are met and then the calculation results are outputted.

In the calculation of the Theis well function, the following approximation formula is used:

$$\begin{cases} \text{while } 0 < u < 1: \\ W(u) = -\ln u - 0.57721566 + 0.99999193u - 0.24991055u^2 \\ \qquad + 0.05519968u^3 - 0.00976004u^4 + 0.00107857u^5 \\ \text{while } u \geq 1:\ W(u) = \dfrac{1}{ue^u}\left(\dfrac{a_0 + a_1 u + a_2 u^2 + a_3 u^3 + u^4}{b_{0+} b_1 u + b_2 u^2 + b_3 u^3 + u^4}\right) \end{cases} \tag{10}$$

where
a_0 = 0.2677737343, a_1 = 8.6347608925, a_2 = 18.059016973, a_3 = 8.5733287401;
b_0 = 3.9584969228, b_1 = 21.09965830827, b_2 = 25.6329561486, b_3 = 9.5733223454.

4.2. Determination of other parameters

The density and specific heat of water vary with temperature. In this study, the water density and specific heat value was calculated according to the vertical average temperature of water gathering segment for each geothermal well, and then substituted into Eq. (3) for use in calculation.

Other values of parameters that could be searched in geothermal well completion reports include :

- thickness of the sandstone of the geothermal reservoir,
- buried depth of the roof of the geothermal reservoir,
- porosity of the sandstone of the geothermal reservoir,
- rock density of the geothermal reservoir,
- rock specific heat,

- vertical average temperature of the geothermal reservoir,
- initial water level height above the surface.

5. Calculation of storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

5.1. Detailed illustration on the calculation of storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

As a case study, this proposed method was applied to Zhangjiapo Formation of Xi'an Depression.

Xi'an Depression is a graben-type depression, located in the Guanzhong Basin.The calculation region covered the south of Weihe Fault to the north of Yuxia-Tieluzi Fault and Chang'an-Lintong Fault and by the east of Yabo Fault, to the west of Chang'an-Lintong Fault and Bahe Fault, with an approximate area of 2005 km^2. It covers the western half and eastern half of Xi'an depression (Fig . 1).

The east of Xi'an Depression, which is in the east of Fenghe Fault with an area of 951 km^2, is mainly the urban area of Xi'an City. For many years, this area has been the concentrated geothermal exploration zone, with many geothermal wells. Large exploitation amounts and rich geothermal geological data have been accumulated.

In the Xi'an Depression, faults are developed in the widely distributed Cenozoic strata. Five formations of geothermal reservoirs exist in the depression at the depth of less than 4,000 m, including Quaternary Pleistocene Sanmen Formation, Neogene Pliocene Zhangjiapo Formation, Neogene Pliocene Lantian Bahe Formation, Neogene Miocene Gaoling Formation, and Paleogene Oligocene Bailuyuan Formation. The following are the estimated thicknesses of each formation: Sanmen Formation >750 m; Zhangjiapo Formation > 1,300 m; the Lantian Bahe Formation > 1,000 m; Gaoling Formation > 1,500 m; and Bailuyuan formation > 500 m. In this study, only the Zhangjiapo Formation was calculated.

In the calculation area of the Xi'an Depression, there are 28 geothermal wells in the Zhangjiapo Formation, of which 27 wells are concentrated in the eastern half of the Xi'an Depression. The eastern half of the Zhangjiapo Formation is suitable for the calculation of storage capacity of geothermal reservoir by weighted element method after element meshing. However, the weighted element method is not suitable for the calculation of the western half, because there is only one geothermal well in the Zhangjiapo Formation. The 27 geothermal wells in the eastern half of the Depression were divided into 77 elements (Fig. 2). The 11 parameters of each node were substituted into the calculation procedure to calculate and output the corresponding data.

5.2. Calculation results of storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

The first and and last elements (i.e. element No. 77) of the eastern half were listed in Columns 2 and 3 in Table 1 because of the length limitation of this paper. The sum of each type of data in the 77 elements is listed in Column 4, while the data for the western half are listed in Column 5. The total values are provided in Column 6.

Conversion of standard coal: If 1t of standard coal is equivalent to 7000 × 10^3 kcal heat, the storage capacity of the geothermal resources can be converted to standard coal. The results are listed in Table 2.

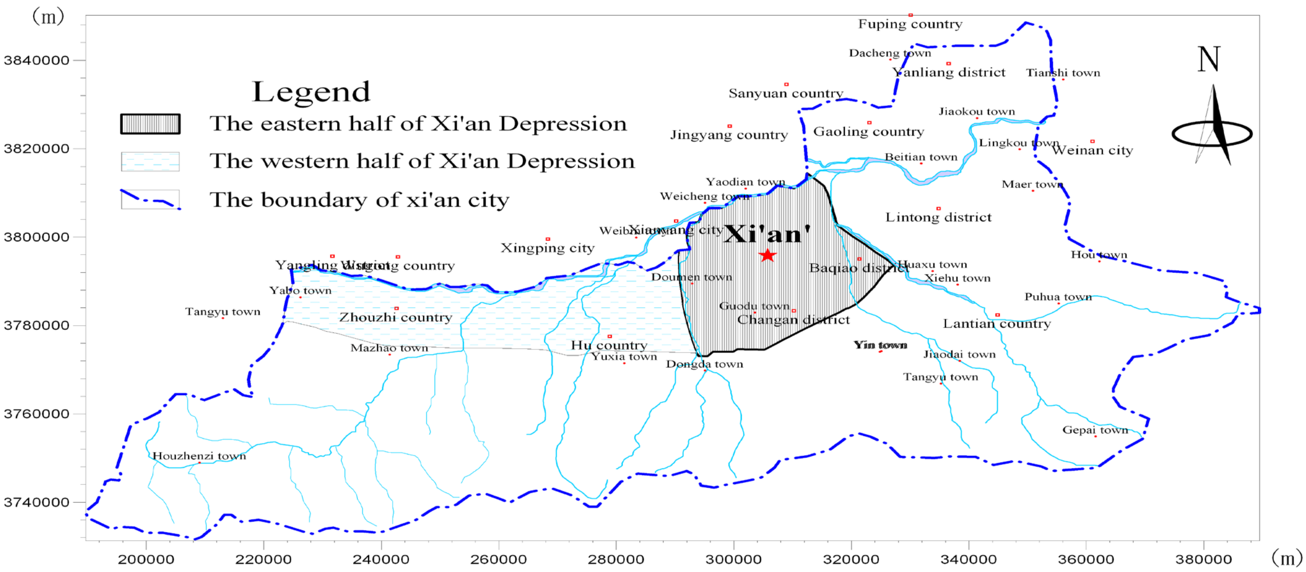

Fig. 1. Calculation range graphic of storage capacity of geothermal resources in Xi'an Depression.

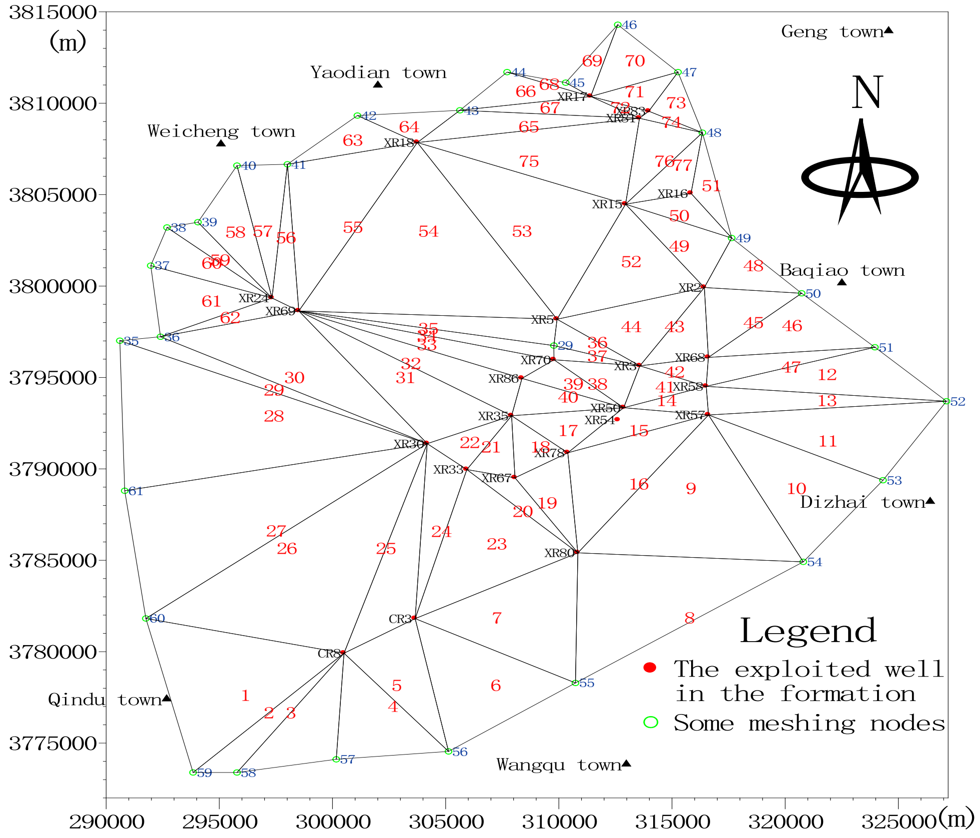

Fig. 2. Meshing graphic of Zhangjiapo Formation in Xi'an Depression.

Table 1
Calculation results of storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

Item	The East of Xi'an Depression			The west of Xi'an Depression	The total of Xi'an Depression
	Element No. 1	Element No. 77	Sum of the eastern half		
Volume storage capacity of geothermal water (10^4 m^3)	52947.34	7769.773	2431253	2426912	4858165
Elastic storage capacity of geothermal water with a drawdown of 130 [m] (10^4 m^3)	187.7996	25.0233	5378.155	5674.638	11052.79
Elastic storage capacity of geothermal water with draw-down to the roof of geothermal reservoir (10 m^3)	1344.645	165.524	34081.63	39891.25	73972.88
The sum of elastic volume storage capacity of geother-mal water (10^4 m^3)	54291.98	7935.297	2465335	2466803	4932138
The heat contained in rocks (10^8 kcal)	47540.14	3940.463	1285568	1185068	2470636
The heat contained in volume storage capacity of geo-thermal water (10^8 kcal)	26243.21	1912.1530	803140.1	660431.9	1463572
The heat contained in elastic storage capacity of geo-thermal water (10^8 kcal)	677.78	40.7357	11345.53	10855.55	22201.08
The total heat contained in storage capacity of geother-mal water (10^8 kcal)	26921	1952.889	814486.1	671287.5	1485774
The total heat contained in geothermal reservoir (10^8 kcal)	74461.14	5893.352	2100054	1856356	3956410
The heat in elastic storage capacity of geothermal water with a drawdown of 130 [m] (10^8 kcal)	93.0824	6.1583	1757.1880	1544.231	3301.419
Area (km^2)	34.89878	4.650077	950.5157	1054.519	2005.035

Table 2
Equivalent standard coal of the storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

Item	The East of Xi'an Depression			The west of Xi'an Depression	The total of Xi'an Depression
	Element No. 1	Element No.77	Sum of the eastern half		
The heat contained in rocks converted into coal (10^4 t)	679.1449	56.29233	18365.26	16929.54	35294.8
The heat contained in water volume storage capacity converted into coal (10^4 t)	374.903	27.31647	11473.43	9434.741	20908.171
The heat contained in water elastic storage capacity converted into coal (10^4 t)	9.682571	0.581939	162.079	155.0793	317.1583
The total heat contained in water storage capacity converted into coal (10^4 t)	384.5857	27.89841	11635.52	9589.821	21225.341
The total heat contained in geothermal reservoir converted into coal (10^4 t)	1063.731	84.19074	30000.77	26519.37	56520.14
The heat in elastic storage capacity of geothermal water with a drawdown of 130 [m] converted into coal (10^4 t)	1.329749	0.087976	25.1027	22.0604	47.1631

As shown in Table 1, the actual geothermal energy that can be effectively exploited and used is 3301.419×10^8 kcal, which is equivalent to standard coal of 47.1631×10^4 t (last line of Table 2).The large scale geothermal exploitation in Xi'an has been conducted for approximately 20 years. The elastic storage capacity of geothermal water contributes to the total exploitation within a drawdown of 130 m. If the average daily exploitation is 0.5×10^4 m^3, the hot water in the Zhangjiapo Formation that has been exploited in the 20 years is 3,650×10^4 m^3. The hot water has been used for bathing, water supply in resorts, and tropical fish breeding. The number is equivalent to 301.419×10^8 kcal, saving the standard coal of 15.7×10^4 t. At present, the Zhangjiapo Formation is still in exploitation in such a scale, which indicates that the result is accurate and reliable.

5.3. Development potential analysis on storage capacity of geothermal resources in Zhangjiapo Formation of Xi'an Depression

Taking the head height at the well completion as the measuring point, at the average drawdown of 130 m, the elastic storage capacity of the Zhangjiapo Formation in Xi'an Depression is 11052.79×10^4 m^3 , accounting for 15% of the total of 73972.88×10^4 m^3 in the Zhangjiapo Formation. If the daily recovery is 0.5×10^4 m^3 as a rough estimation (currently, the total daily recovery of 5 geothermal reservoirs in Xi'an Depression is 1×10^4 m^3, of which, the water recovery of the Zhangjiapo Formation is less than 50%), the exploitation can be maintained for 60 years with elastic storage capacity of the Zhangjiapo Formation at the average drawdown of 130 m. The mining can be maintained for 405 years with elastic storage capacity at the drawdown to the geothermal reservoir roof.

If the geothermal recovery rate of the geothermal reservoir is 10%, which is 395641.0×10^8 kcal and is 18 times more than the geothermal energy of the elastic storage capacity (22201.08×10^8 kcal), the mining lifespan is 7217 years. If the heat of geothermal reservoir from deep heat sources is also taken into account, the development potential would be much larger, and the recovery time would be doubled.

As 1t of standard coal was converted into 7000×10^3 kcal heat, the total heat of geothermal resources 3956410×10^8 kcal was equivalent to standard coal of 56520.14×10^4 t. Under the current conditions of exploitation technology, the actual geothermal energy that can be effectively exploited and used is 3301.419×10^8 kcal, or standard coal of 47.1631×10^4 t.

6. Conclusion

This paper proposed weighted element method to improve the calculation accuracy of storage capacity of geothermal reservoir. This method fully exploits all geothermal wells in the calculation region, and the calculation region of every three neighboring geothermal wells was divided into calculation elements. The whole calculation region of the distribution parameters was discretized into regions with independent lumped parameter in each element. The arithmetic mean of three node parameters in each element was used as the lumped parameter and the block with the same set of parameters was divided into calculation regions as small as possible. The effect of one element as well as its parameters in the whole calculation region depends on the weight of area of this element in the whole calculation area. The weighted element method can be used to calculate the volumetric water storage capacity of geothermal fluid, elastic release storage capacity, geothermal storage capacity of volume water, geothermal energy storage capacity of elastic releasing water, geothermal storage capacity of geothermal reservoir rocks for each element, respectively. The storage capacities of various elements and the entire calculation regions can be calculated through superposition. The second part of the paper demonstrates its application to the Zhangjiapo Formation of Xi'an Depression. The data of 28 existing geothermal wells were adopted to calculate the storage capacity of geothermal resources. If the geothermal energy recovery is set as 10%, under the current efforts of exploitation, the geothermal energy contained in the geothermal reservoir can be extracted for more than 7,000 years; while under the current conditions of exploitation technology, the actual geothermal energy that can be effectively exploited and used is 3301.419×10^8 kcal, or equivalent to standard coal of 47.1631×10^4 t.

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Appendix

The main statement of the elastic storage coefficient μ* computation procedure is provided as follows:

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.........
50    a=0
      b=0
      c=0
      e=0
      f=0
      do 10 i=1,n
      u=s0*r*r/t0/t(i)/4
      write (*,*) 'u=',u
      if (u.gt.1) goto 20
      wu=((((0.00107857*u-0.00976004)*u+0.05519968)*u
    *   -0.24991055)*u+0.99999193)*u-0.57721566-dlog(u)
      goto 30
20    y=(((u+8.5733287401)*u+18.059016973)*u+
        8.6347608925)*u
    *  +0.2677737343
      w=(((u+9.5733223454)*u+25.6329561486)*u+
        21.0996530827)*u
    *  +3.9584969228
     wu=1/exp(u)/u*(y/w)
30    s10(i)=q/(4*3.1415926*t0)*wu
      ss(i)=-q*exp(-u)/s0/t0/4/3.1415926
      a=a+st(i)**2
      b=b+st(i)*ss(i)
      c=c+ss(i)**2
      e=e+st(i)*(s1(i)-s10(i))
      f=f+ss(i)*(s1(i)-s10(i))
10    continue
      ds=(a*f-b*e)/(a*c-b**2)
      dt=(e-b*ds)/a
      t0=t0+dt
      s0=s0+ds
      if (abs(dt/t0).lt.0.001) goto 40
      goto 50
40   write(*,*)'t=',t0,'(m2/d)    s=',s0
………
```

The variables in the procedure:

s0 — *S* initialization
t0 — *T* initialization
q — *Q* (m^3/d)
r — The distance from the monitoring well to the pumping well
n — The monitoring times of the water level degration
t(i) — The monitoring time of the water level degration (d)
s1(i) — The water level degration value of of the monitoring well
W(u) — Theis well function
u — the independent variable of W(u).