Tidally Induced Water Temperature Change in Artesian Wells

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Water temperature observation in wells as a precursor observation project in China aims to capture stress-strain information during the preparation of earthquakes. The study of the water temperature tidal effect has important significance for water temperature tidal effect is both a reflection of stress-strain in crust and an interference factor of precursor observations. With a view of thermal conditions in artesian wells, the paper holds that there are two mechanisms for interpreting tidally induced water temperature changes in artesian wells. Namely, thermal conduction mechanisms and thermal convection mechanism. The paper then derives the quantitative relationship between water temperature and tidal volumetric strain changes in an ideal artesian well. Finally, the water temperature tidal effect in the Benxi artesian well is analyzed. The results show that the water temperature tidal effect in Benxi well is the result of joint action of thermal conduction mechanism and thermal convection mechanism, in which thermal conduction mechanism plays a leading role.

Key words: Artesian well; Water temperature; Earth tide; Thermal conduction; Thermal convection; Benxi area

INTRODUCTION

The relationship between groundwater temperature micro-dynamic and crustal stress-strain or even earthquakes has been an impotent scientific issue for years. Groundwater temperature changes preceding earthquakes were reported in many studies (Shimamura et al., 1984; Fu Zizhong, 1988; Mogi et al., 1989; Che Yongtai et al., 1996; Che Yongtai et al., 2008). How the changes as earthquake precursors are confirmed is the key to solving the issue. Tidal effect has a close relationship with crustal stress-strain and is useful for earthquake precursor recognition. Studying...
the mechanisms of groundwater temperature tidal effect is meaningful because it helps us understand thermal condition changes and thermal transfer modes of certain ground areas under stress loadings (Cermak et al., 2008, 2009). It also provides better appreciation of how aquifers respond to earth tides (Rosaev et al., 2003; Esipko et al., 2007) and clarifies the ability of groundwater temperature responses to crustal stress-strains (Furuya et al., 1988; Kitagawa et al., 1996). As the groundwater temperature tidal effect is influenced by many factors, quantitative analysis on it is significant, thus becoming a research hotspot in recent years.

From the mid-1980s, China started to construct groundwater temperature observation networks for earthquake monitoring and prediction. There are currently hundreds of water temperature observation wells. According to existing data, we find that over 30 wells have obvious water temperature tidal effects. These wells and their data lay the foundation for further study. We also find that water temperature is more sensitive to earth tides in artesian wells rather than in non-artesian ones. Based on the review of relevant studies of water temperature tidal effects in artesian wells (Furuya et al., 1988) and Zhang Zhaodong et al. (2002) believe that the effect relates with groundwater flow changes caused by earth tides. Koizumi (1990) analyzed the relationship between groundwater flow and temperature changes in an artesian well in Japan and deduced their quantitative relationship. Zhang Yongxian et al. (1991) obtained the same results in their study. However, the quantitative analysis of water temperature tidal effects in artesian wells is still rare in literature. In this paper, we quantitatively analyze the mechanism of water temperature tidal effects in artesian wells. We then use the results to interpret the water temperature tidal effect in the Benxi artesian well.

1 THERMAL STATE IN ARTESIAN WELLS

Before analyzing the mechanisms of water temperature tidal effects in artesian wells, the thermal state in artesian wells need to be analyzed. The water in artesian wells outflow constantly from discharge outlets and the wells have heat exchange with the outside environment from the water surface. The thermal state in artesian wells may therefore be affected by many factors. The factors that influence long-term dynamics of water temperature include climate, rainfall, surface water infiltration, different aquifer water mixing and so on. The factors that influence micro-dynamics of artesian water may include three factors as follows:

1. When water outflows from an artesian well, there will be a temperature difference between the well water and surrounding rock, which arouses thermal conduction. The basic thermal conduction equation of well water and its surrounding rock is (Che Yongtai et al., 2008)

\[
\frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial r^2} + \frac{\partial T}{r \partial \phi} + \frac{\partial^2 T}{\partial \phi^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]

where \( T \) is the temperature, \( k \) is the time of thermal conduction, \( r \) is the radial distance from the well wall to the outside in cylindrical coordinates, \( \phi \) is the angle in cylindrical coordinates, and \( T \) is thermal conductivity.

2. As temperature gradient and water movement exists in an artesian well, it will produce thermal convection. It includes two cases. One is that the well water has heat exchange with the outside environment, so the water in the well has different temperature to the water in the aquifer. The temperature gradient then exists in the horizontal direction, which is why thermal convection occurs when water moves between the well and the aquifer. The other is that the well water has heat exchange with the surrounding rock with the temperature gradient existing in the vertical direction, and when water moves in the well, it will also bring about thermal convection. The basic thermal convection equation in well-aquifer and in well is (Che Yongtai et al., 2008)
\[
\frac{\partial}{\partial x_i}(v_i \rho C_{\rho} T) = \rho C_{\rho} \frac{\partial T}{\partial t} \tag{2}
\]

where \(x_i\) is the migration distance of the water flow, \(v_i\) is the water velocity, \(\rho\) is the water density, \(C_{\rho}\) is the heat capacity of water, \(T\) is the temperature and \(t\) is the time of thermal convection.

(3) If the temperature difference exists between the water and atmosphere at the water surface of the well, there will be thermal diffusion. The impact of thermal diffusion is limited, usually no more than tens of meters. The basic thermal diffusion equation between the well water and atmosphere is (Che Yongtai et al. 2008)

\[
q = \alpha(T_w - T_a) \tag{3}
\]

where \(q\) is the heat flux value, \(T_w\) is the interface water temperature, \(T_a\) is the interface atmosphere temperature, \(\alpha\) is the interface thermal diffusion coefficient.

For an artesian well, the dynamics of water temperature at a certain depth has close relationship with the condition of the aquifer, water temperature gradient, temperature probe position and so on. Therefore, when analyzing the temperature-related phenomenon and its mechanism in artesian wells, all factors need to be reasonably considered.

2 TIDAL EFFECT ON WATER TEMPERATURE IN ARTESIAN WELLS

2.1 Mechanisms of Tidal Effect on Water Temperature

According to the thermal state in artesian wells, we hold that there exists two mechanisms for interpreting the tidal effect on water temperature. One is the thermal conduction mechanism. It can be interpreted as follows. Tidal volume strain excites the pore pressure fluctuations in the aquifer. The fluctuations then drive the aquifer water to flows between the aquifer and the well, which leads to the change of well water flow rate. In the process of water outflow from the well because of thermal conduction between well water and surrounding rock, the well water temperature will change. The well water temperature change is directly related with the changes of the well water flow. That is, if the well water temperature is higher than the surrounding rock temperature, when well water flow becomes smaller, the surrounding rock will receive more heat from the well water and water temperature will reduce. When well water flow becomes larger, the surrounding rock will draw less heat from the well water and water temperature will rise. Tidal volume strain causes pore pressure fluctuation leading to well water flow change. That is, the well water flow changes with the change of well water temperature.

The other is the thermal convection mechanism. It can be interpreted as follows. Tidal volume strain excites the pore pressure fluctuation in the aquifer. The fluctuations then force aquifer water to flow between the aquifer and the well making the flow velocity change. The change of velocity will lead to thermal convection change both in the well-aquifer and in the well. The well water temperature will change when thermal convection changes. The well water temperature change is directly related with the change of the flow velocity. That is, if well water temperature is higher than the surrounding rock temperature, when flow velocity becomes smaller, thermal convection will become weaker in the well-aquifer and in the well, and water temperature will reduce. When flow velocity becomes larger, thermal convection will become stronger and water temperature will rise. Tidal volume strain causes fluctuation of pore pressure leading to the change of flow velocity. Flow velocity changes will cause well water temperature to change. That is, the well water temperature changes with the change of tidal volume strain.

Both of the mechanisms can explain the water temperature tidal effect in artesian wells.
Considering the following reasons only the thermal conduction mechanism is quantitatively analyzed in this paper. First, the thermal state is complex in artesian wells and may be different at different depths in a well. As the constitutive relation is relatively clear in the thermal conduction mechanism than that in thermal convection, quantitative analysis on the thermal conduction mechanism is an effective method. Another reason is that we hold that thermal conduction may be dominant in some artesian wells with large water flow, which is unanimous with some researchers’ studies (Zhang Yongxian et al., 1991; Koizumi, 1990; Mogi et al., 1989).

2.2 Analysis of Thermal Conduction Mechanism

Assuming that tidal volumetric strain change causes pore pressure change, then the pressure change causes water flow change and the water flow change induces water temperature change. The paper derives the quantitative relationship between the tidal volumetric strain change and water temperature change in an ideal artesian well. The amount of water temperature change by thermal conduction mechanism can be obtained based on this.

The paper adopts an ideal physical model of artesian well water temperature observation (Fig. 1) with the assumptions that: ① groundwater micro-dynamic is relatively stable and the groundwater temperature in the recharging aquifer remains unchanged. The tide-induced groundwater discharge changes slowly and the process is quasi-static; ② ground temperature is constant in the horizontal direction and increases uniformly in the vertical direction; ③ the change of well water temperature with water flow is caused by thermal conduction of well water when flowing through between well casing and surrounding rock; and ④ the current in the wells is steady-state ideal fluid. Based on these assumptions, the quantitative relationship between the tidal volumetric strain change and water temperature change can be derived as follows.

![Fig. 1](image)

An ideal physical model of an artesian well

Volume strain change causes expansion and contraction of the aquifer media, thus fluctuating the pore pressure of aquifer media. The pore pressure change ($\Delta P$) caused by volume strain change ($\Delta \varepsilon$) can be expressed (Bredehoeft, 1967) as:

\[
\Delta P = \frac{\mu}{\rho} \cdot \Delta \varepsilon
\]
\[ \Delta P = -\frac{\rho g}{S_s} \Delta \varepsilon \]  \hfill (4)

Where \( \rho \) is the density of water, \( g \) is the acceleration due to gravity, \( S_s \) is the specific storativity of aquifer. The negative sign indicates the decrease of pore pressure with the expansion of the aquifer medium and the increase of pore pressure with the contraction of the aquifer medium.

According to hydro-dynamic theory, the pore pressure at the top of the aquifer can be expressed as

\[ P = \rho g (h + h_0) + \frac{1}{2} \rho u^2 + P_a \]  \hfill (5)

where \( h \) is the distance between the water surface and the discharge outlet and is also the water level of artesian wells in the Chinese water level observation network. \( h_0 \) is the distance between the centre line of the discharge outlet and the top of the aquifer; \( u \) is the flow velocity at the discharge outlet; \( P_a \) is the barometric pressure at the water surface.

The water flow \( Q \) at the discharge outlet can be expressed as

\[ Q = A u \]  \hfill (6)

where \( A \) is the cross sectional area of the discharge outlet.

Assuming the well water as steady-state ideal fluid, the relationship between \( h \) and \( u \) is

\[ h = \frac{u^2}{2g} \]  \hfill (7)

From equation (5) – (7) we get

\[ P = \frac{\rho Q^2}{A^2} + \rho g h_0 + P_a \]  \hfill (8)

Assuming that the well water temperature change with flow rate is caused by heat conduction of well water when flowing between surrounding rock and the well casing, the relationship between water temperature and water flow is (Koizumi, 1990)

\[ T(z) = T_0 - \gamma z + \frac{\gamma Q_1}{E} \left(1 - \exp\left(-\frac{E}{Q_1 z}\right)\right) \]  \hfill (9)

where \( z \) is the distance between the temperature probe and the top of the aquifer; \( T(z) \) is the water temperature at depth \( z \); \( T_0 \) is the temperature of the recharging aquifer; \( y \) is the geothermal gradient; \( Q_1 \) is the well water flow; \( E = \frac{2\pi a k}{\rho c d} \) is the internal radius of the well; \( k \) is the thermal conductivity of the well casing; \( c \) is the heat capacity of the groundwater; and \( d \) is the thickness of the well casing.

In the artesian well (Fig. 1), the well water flow changes caused by tidal volume strain changes consist of flow changes in the discharge outlet and the water level changes \( \Delta h \). The paper assumes that the water flow at the discharge outlet is equal to the well water flow when the well water flow is relatively large. From equation (4), (8) and (9) we can obtain the relationship between \( \Delta T \) and \( \Delta \varepsilon \) in quasi-static process as follows

\[ \Delta T = -\frac{\gamma A^2 g}{2E S_s Q_0} \left(1 - \exp\left(-\frac{E}{Q_0 z}\right)\right) \Delta \varepsilon \]  \hfill (10)

Where \( Q_0 \) is the average value of the water flow at the discharge outlet. The first negative sign in the right side of formula indicates that the water temperature decreases when the aquifer medium expands and the water temperature increases when the aquifer medium contracts.

Equation (10) shows that the ability of water temperature in response to earth tides is mainly related with the specific storativity of the aquifer, geothermal gradient, well water flow, radius of the well and temperature probe position. In particular, the ability of the water temperature in
response to earth tides will be strong if the distance between the temperature probe and the observing aquifer is great and the radius of the well is small.

3 TIDAL EFFECT ON WATER TEMPERATURRED IN THE BENXI ANTESIAN WELL

Based on the analysis in section 2, the paper takes the Benxi artesian well as an example to discuss the mechanisms of tidal effect on water temperature. First, based on the analysis of the thermal conduction mechanism, we compute the ratio of water temperature changes $\Delta T$ to tidal volume strain changes $\Delta \varepsilon$ using the Benxi well data. Then another ratio of $\Delta T$ to $\Delta \varepsilon$ is gained from the harmonic analysis of Benxi well’s water temperature observation data. Finally, the mechanisms of water temperature tidal effect are discussed after comparing the two results.

The Benxi well locates in Taigou village, Qiaotou town, Benxi city, Liaoning Province, P. R. China. The location is at 123. 70 degrees east and 41. 29 degrees north. The elevation of the wellhead is 173. 34m, and the depth of the well is 1213. 46m. The area where the Benxi well locates is in the junction between the east extension of E-W trending Yinshan tectonic belt and the second giant uplift of the Neocathaysian, belonging to the Taizihe depression zone. The observing aquifer water of Benxi well is fissure confined water. The well has two aquifers, one at 600m, the other locates between 952m ~ 957m. When the water from the two aquifers mixes and flows to the discharge outlet, the water temperature is about 20℃ (Sun Xiaolong, 2009). The well adopts the SZW-1A digital thermometer to measure the temperature, and the temperature probe is placed 37m below the ground surface. The thermometer’s resolution is $\leq 0. 0001^\circ C$, the observation accuracy is $\leq 0. 05^\circ C$, the short-term stability is $\leq 0. 0001^\circ C / d$, the long-term stability is $\leq 0. 001^\circ C / a$ and the sampling rate is 1 time/min (CEA, 2001).

According to the power spectrum estimation, diurnal and semidiurnal periodic variations exist in the water temperature data of the Benxi well (Fig. 2 (a) & (b)) showing significant tidal effects on water temperature of the Benxi well. Besides, the dynamics of the water level is similar to water temperature (Fig. 2 (c) & (d)) showing significant tidal effects too.

3.1 Analysis of Thermal Conduction Mechanisms in the Benxi Well

Using the analysis results of thermal conduction mechanisms in section 2, we compute the ratio of water temperature changes $\Delta T$ to tidal volume strain changes $\Delta \varepsilon$ as:

$$\frac{\Delta T}{\Delta \varepsilon} = -\frac{\gamma A^2 g}{2ES_zQ_0} \left(1 - \exp\left(-\frac{E}{Q_0}z\right)\right)$$  \hspace{1cm} (11)

Based on the Benxi well data, the parameter values in equation (11) are as follows: Thermal conductivity $k = 0. 3 J/(s \cdot cm \cdot ^\circ C)$, internal radius of the well $a = 8. 9 cm$, density of water $\rho = 1. 0 g/cm^3$, heat capacity of the groundwater $c = 4. 2 J/(g \cdot ^\circ C)$, thickness of the well casing $d = 0. 3 cm$, then $E = \frac{2 \pi ak}{\rho cd} = 13. 31 cm^2/s$. Taking the section of the Benxi well that is under the depth of 600m as a big aquifer, then $z = 5. 63 \times 10^4 cm$. The measured water flow of the Benxi well is $Q_0 = 150 cm^3/s$ which meets the requirement of relatively large water flow. According to the values of $z$ and $Q_0$ in equation (11) is equal to zero, then equation (11) can be simplified as

$$\frac{\Delta T}{\Delta \varepsilon} = -\frac{\gamma A^2 g}{2ES_zQ_0}$$  \hspace{1cm} (12)

In equation (12), only the specific storativity of aquifer $S_z$ is not known. From equation (6) ~ (9) we can obtain
Fig. 2

(a) Water temperature data in the Benxi artesian well from December 2007 to January 2008. (b) Power spectrum of the water temperature data. (c) Water level data in the Benxi artesian well from December 2007 to January 2008. (d) Power spectrum of the water level data

\[ P = 2 \rho gh + \rho gh_0 + P_a \]  

(13)

If the ocean tide is not considered and barometric pressure influence is corrected, the water level change is only caused by earth tides. From equation (13) and (4) we can obtain

\[ \Delta P = - \frac{\rho g S_s}{\Delta \varepsilon} = 2 \rho g \Delta h \]  

(14)

and

\[ S_s = 1/(2 \frac{\Delta h}{\Delta \varepsilon}) \]  

(15)
Where $\Delta h$ is the variation of water level.

Harmonic analysis of the Benxi well’s water level observation data can get the ratio of $\Delta h$ to $\Delta \varepsilon$ in equation (15). In the method of harmonic analysis, the theoretical value is tidal volume strain value (magnitude is $10^{-9}$). The results of harmonic analysis then represent water level changes caused by the theoretical unit of tidal volume strain that is $\Delta h/\Delta \varepsilon$.

The paper chooses the water level integral point data of the Benxi well from November 2007 to April 2008. Harmonic analysis of the data after barometric pressure correction shows that the main waves with large amplitude have high precision such as $O_1$ and $K_1$ diurnal waves $\Delta h/\Delta \varepsilon$. The results of harmonic analysis then represent water level changes caused by the theoretical unit of tidal volume strain that is $\Delta h/\Delta \varepsilon$.

Harmonic Analysis of Water Level Data of Benxi Well

We can obtain another ratio $\Delta T/\Delta \varepsilon$ by harmonic analysis of the Benxi well water temperature data.

On the principles of smooth, continuous, and less interference, we choose the data of the Benxi well from November 2007 to April 2008 for the analysis (Fig. 3). Some pretreatment was applied to the original data that is completing a small amount of missing data by interpolation, eliminating the sudden jump changes caused by calibration and adjusting equipment.
First, we choose the data of the Benxi well from November 2007 to April 2008 for the analysis. The short-period and long-period changes are isolated from the water level, water temperature and barometric pressure data using the Piel Zaitsev filtering method (Zhang Guomin et al., 2001). The results are shown in Fig. 3. From Fig. 3(a) ~ (c) where water level and water temperature have the same daily fluctuations as the theoretical gravity tidal values. From Fig. 3(e) ~ (g) the long-period fluctuations of water temperature have similar morphology with that of the water level and the long-period fluctuations of water temperature and water level have reverse morphology with that of barometric pressure. Based on the results, we hold that barometric pressure change affects water level change and the water level change affects water temperature change thus the barometric pressure change indirectly affects water temperature change. Hence before
Harmonic analysis is carried out to eliminate the influence of barometric pressure change on water temperature dynamics. The influence of barometric pressure change on water temperature can be eliminated with the same method as that of water level (Du Pinren, 1991), namely:

\[ T(t) = T_0(t) - B P_a(t + \Delta t) \]  

(16)

where \( T_0(t) \) is the original water temperature, \( T(t) \) is the water temperature after barometric pressure correction, \( B \) is the barometric pressure efficiency on water temperature change, and \( \Delta t \) is the lag time.

The barometric pressure efficiency \( B \) in equation (16) denotes the effect of barometric pressure change on water temperature change, defined as:

\[ B = -\frac{dT}{dP_a} \]  

(17)

Using the Piel Zaitsev filtering method, short-period and long-period changes are isolated from water temperature and the barometric pressure data from November 2007 to April 2008 of the Benxi well. Using regression analysis, we can obtain the barometric pressure efficiency \( B \) as 3.21 m℃/hPa (The correlation coefficient is -0.813, greater than the level of significance test).

The \( \Delta t \) in equation (16) denotes the lag time that water temperature changes after barometric pressure changes. The \( \Delta t \) can be estimated by lag correlation analysis of the long-period pressure and water temperature changes. According to the data of the Benxi well from November 2007 to April 2008, the lag time \( \Delta t \) equals 6 hours.

Given the barometric pressure efficiency \( B \) and lag time \( \Delta t \), the influence of barometric pressure change on water temperature can be eliminated basing on equation (16).

The paper chooses the water temperature integral point data of the Benxi well from November 2007 to April 2008 for the harmonic analysis using Venedikov’s method. In the method, the theoretical value is the tidal volume strain value (magnitude is \( 10^{-9} \)). Therefore, the results by harmonic analysis represent the water temperature change induced by unit theoretical tidal volume strain, that is \( \Delta T/\Delta \varepsilon \).

The harmonic analysis of the data after barometric pressure correction is shown in Table 1. From the harmonic analysis, we know that:

1. Waves with large amplitude have high precision, such as \( O_1 \) and \( K_1 \) in diurnal waves and \( M_2 \) and \( S_2 \) in semidiurnal waves.

2. The water temperature of the Benxi well is sensitive to tidal strain and the average tidal factor of \( O_1 \), \( K_1 \), \( M_2 \), and \( S_2 \) waves can reach 1.8240 m℃/10^{-9}. Take the average to denote \( \Delta T/\Delta \varepsilon \), then we get:

\[ \frac{\Delta T}{\Delta \varepsilon} = 1.8240 \text{ m℃/}10^{-9} \]

### Table 1 Results of harmonic analysis of water temperature data in Benxi artesian well

<table>
<thead>
<tr>
<th>No.</th>
<th>Partial Wave</th>
<th>Tidal Factor (m℃/10^{-9})</th>
<th>Phase Lag (°)</th>
<th>Maximum amplitude (m℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q₁</td>
<td>1.8204 ± 0.1364</td>
<td>-1.9029 ± 4.3481</td>
<td>2.9795 ± 0.0996</td>
</tr>
<tr>
<td>2</td>
<td>O₁</td>
<td>1.8992 ± 0.0257</td>
<td>-4.5264 ± 0.7769</td>
<td>14.7021 ± 1.002</td>
</tr>
<tr>
<td>3</td>
<td>M₁</td>
<td>2.3720 ± 0.3763</td>
<td>-21.7575 ± 9.6354</td>
<td>1.3971 ± 4.039</td>
</tr>
<tr>
<td>4</td>
<td>K₁</td>
<td>1.5056 ± 0.0192</td>
<td>-9.34922 ± 0.7496</td>
<td>15.152 ± 0.7674</td>
</tr>
<tr>
<td>5</td>
<td>J₁</td>
<td>2.1579 ± 0.3176</td>
<td>-13.6488 ± 8.6760</td>
<td>1.4685 ± 1.2884</td>
</tr>
<tr>
<td>6</td>
<td>OO₁</td>
<td>1.8215 ± 0.4351</td>
<td>-14.0963 ± 14.5233</td>
<td>0.7500 ± 0.9267</td>
</tr>
<tr>
<td>7</td>
<td>2N₂</td>
<td>2.2620 ± 0.4401</td>
<td>-8.6529 ± 4.5707</td>
<td>0.6032 ± 0.1726</td>
</tr>
<tr>
<td>8</td>
<td>N₂</td>
<td>1.6911 ± 0.0480</td>
<td>7.07883 ± 1.6387</td>
<td>3.3720 ± 0.2507</td>
</tr>
<tr>
<td>9</td>
<td>M₂</td>
<td>1.8093 ± 0.0086</td>
<td>10.18008 ± 0.2713</td>
<td>18.9945 ± 0.2543</td>
</tr>
<tr>
<td>10</td>
<td>L₂</td>
<td>2.2569 ± 0.3187</td>
<td>19.15223 ± 7.7528</td>
<td>0.4854 ± 0.2511</td>
</tr>
<tr>
<td>11</td>
<td>S₂</td>
<td>2.0817 ± 0.0159</td>
<td>8.541017 ± 0.4457</td>
<td>9.5228 ± 0.2357</td>
</tr>
<tr>
<td>12</td>
<td>M₃</td>
<td>2.6066 ± 1.2545</td>
<td>-22.3464 ± 27.6328</td>
<td>0.2698 ± 0.9003</td>
</tr>
</tbody>
</table>
\( \Delta T/\Delta \varepsilon \) equals to 1.0762 m\(^{\circ}\)C/10\(^{-9}\) computed by equation (16) while it equals 1.8240 m\(^{\circ}\)C/10\(^{-9}\) by harmonic analysis of water temperature data. Both results show that in the aspect of the magnitude, the thermal mechanism is the main mechanism of water temperature tidal effects in the Benxi well. However, the magnitude computed equation (16) is less than that by harmonic analysis. The difference can be interpreted as the contribution of the thermal convection mechanism. The tidal effect on water temperature in the Benxi well is therefore the result of joint action of both thermal conduction mechanisms and thermal convection mechanisms in which the thermal conduction mechanism is dominant.

4 SUMMARY AND DISCUSSION

The following conclusions are drawn after analyzing the tidal effect on water temperature in the Benxi artesian well.

(1) Tidal effects on water temperature in an artesian well is a real response of local aquifers to stress-strain. Its mechanisms include thermal conduction and the thermal convection mechanisms. The result of harmonic analysis of water temperature data after barometric pressure correction can reflect tidal influence on well water temperature.

(2) In the thermal convection mechanism of water temperature tidal effects in artesian wells, the ability of water temperature in response to earth tides relate mainly to the specific storativity of the aquifer, geothermal gradient, well water flow, radius of the well and temperature probe position.

(3) For some artesian wells with large water flow, the tidal effect on water temperature is the result of both the thermal conduction mechanism and the thermal convection mechanism in which thermal conduction mechanism is dominant.

These conclusions are preliminary. In-depth study is needed to investigate the tidal effect on water temperature in artesian wells such as quantitative analysis of thermal convection mechanisms and phase lag. In addition, the water temperature tidal effect in non-artesian wells is common and only by systematically studying the mechanisms of these effects in non-artesian wells can we thoroughly understand the mechanisms of water temperature tidal effects in wells.

The authors gratefully acknowledge Che Yongtai, Wang Haiyan and Tang Jiu'an for their kind help and support.


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