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Analysis of phase lead "anomalies" in the tidal response of groundwater levels

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【Abstract】The tidal response to the groundwater level refers to an aquifer under the influence of tidal forces, the pressure head (pore pressure) within the aquifer produces changes that drive the alternating transportation of water between well-aquifers, causing the rise and fall of the water level in the wells. Considering the driving process of force and seepage of water, the groundwater level response should only have a phase lag compared to the Earth's solid tides. However, the actual observation data show that the phase of the groundwater level tidal response exceeded that of the theoretical gravity tides, which is not in accordance with the commonly occurring mechanical process of the phenomenon. Using the theory of trans-current recharge,

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the seepage of aquifer water was decomposed into lateral and vertical transport, and the two kinds of "lagging" transport processes were superimposed to obtain the final groundwater level tidal response, which may appear as an anomalous phenomenon in which the phase is over the front after superposition. Taking the Lugu Lake well as an example, before the Wenchuan earthquake, the phase of groundwater level was ahead of the theoretical solid tide, indicating the existence of a transgressive aquifer, whereas the groundwater level tidal factor declined from 0.28 mm/uGal before the earthquake to 0.23 mm/uGal after the earthquake. The phase, from 15 min ahead in pre-earthquake to 15 min lagged after the earthquake, combined with the theoretical analysis it can be seen that the Wenchuan earthquake led to develop the new fissure in the Lugu Lake well, thus permanently altering its aquifer response and changing the permeability of the aquifer. However, the subsequent earthquakes did not produce new fissures; only the seismic waves caused by the stress redistribution process were observed. This co-seismic response of the groundwater level shows a step-down phenomenon, phase analysis of the groundwater level has scientific significance for the study of well-aquifer conditions and well-borehole seismic capacity.

【**Key Words**】Groundwater level tidal; Tide factor; The phase; co-seismic response

1. Introduction

The quantitative analysis of groundwater levels in unconfined boreholes as affected by Earth solid tides and atmospheric pressure is a classical problem in the hydrogeological and seismic subsurface fluid disciplines. Efforts have been made for

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the theoretical calculations and characterization (Gulley et al., 2013; Liu et al., 2017; Lee et al., 2017; He et al., 2020; Yan et al., 2020; Ma et al., 2023). Earth solid tides are characterized by fixed periods and amplitudes, and the tidal response of groundwater level can be conveniently utilized for quantitative calculation of well-aquifer structural parameters. Cooper et al. (1965) derived an equation of motion for the water column in the well and a method for the calculation of the aquifer transmissivity (T) and aquifer storage rate (S). The groundwater level has zero delay property for ground vibration in a certain frequency range (He et al., 2017), and the groundwater level tidal response has the same frequency as the Earth's solid tides. It is expressed as a sum of harmonics, which only differs in amplitude and phase (Cooper et al., 1965). Hsieh et al. (1987) gave a formula for calculating the amplitude and phase of the tidal response of the water level in wells. The amplitude of the vibration of the water level in wells is mainly affected by the characteristic parameters of elastic deformation of the aquifer, such as Skempton's coefficient, bulk modulus, and Poisson's ratio (Ding et al., 2015；Arditty et al., 1978; Bredehoeft, 1967; Burbey, 2010; Sato et al., 2006; Gao et al., 2020; Van der Kamp and Gale, 1983；Allègre et al., 2016); and the phase is mainly related to the water flow properties of the aquifer, such as permeability (Zhu et al., 2021; Elkhoury et al., 2006; Lai et al., 2014; Shi et al., 2014; Xue et al., 2013; Zhu, 2021).

Assuming that the aquifer is confined, laterally extended, homogeneous, and isotropic, Hsieh et al. (1987) utilized the diffusion equation to derive the phase lag of the tidal response of the water level in the well as a function of aquifer permeability, storage rate, and Earth's solids tides, and there is always a phase lag in water level tidal response of wells because it takes a certain amount of time for the fluids in the

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aquifer to respond to the tidal force and flow into or out of the wells. Chinese scholars have also obtained a similar understanding through theoretical analysis, that is, the inelastic response of the aquifer system to the tidal force leads to a phase difference in the tidal response of the water level in the wells, the size of which mainly depends on the radius of the borehole and the permeability of the aquifer (Zhang et al., 1991; Zhou et al., 1993), but there is no reasonable explanation for the phase overshooting of the tidal response of the wells' water levels. Maas and De Lange (1987) derived the phase shift and attenuation equations in the case of a weakly permeable layer overlying a single aquifer using the superposition principle. Studies comprehensively show that phase lead in the tidal response of groundwater level is due to the semi-confined aquifer with weakly permeable water quality. Studies on the conditions for the existence of phase lead have been carried out using numerical simulations from the theoretical aspect by above authors; however, reports on how to reflect this in the analysis of the actual data and carry out response decomposition of the different layers of the aquifer from the actual observation data of the water level of wells are lacking. In the present study, our efforts are to explain the phase lead of the tidal response of the groundwater level by combining the actual situation of the borehole and groundwater level observation from China Earthquake Networks Center.

The water level data from the Lugu Lake seismic station (51306, Figure 1) (N27.73°, E100.85°) is considered as an example for analysis. This station exposed strata is sandstone of the upper diamictic Black Mud Whistle Formation (P2h) and the sand and gravel layers of alluvial, flood, lacustrine, and slope deposits. Tectonically, it is located in the two flanks of the Yanyuan Arc Tectonic Belt, and the nearby fractures mainly include the Dog Drilling Cave - Cat's Home Village, Gaizu-Xizhu, and Bleaching fractures. The fracture in this region is a positive fracture. The depth of the

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borehole is 200.7 m, with 61 m of clay cover, under which is tuff. The depth of the casing is 74.2 m, and process of stopping water is adopted by the piston pressure of the casing reserved hole in the bottom section of the borehole until the cement slurry is returned from the ground to reduce the interference of the surface water on the water level of the borehole. The pumping experiment at the borehole completion showed that the permeability coefficient was 0.135 m/d.

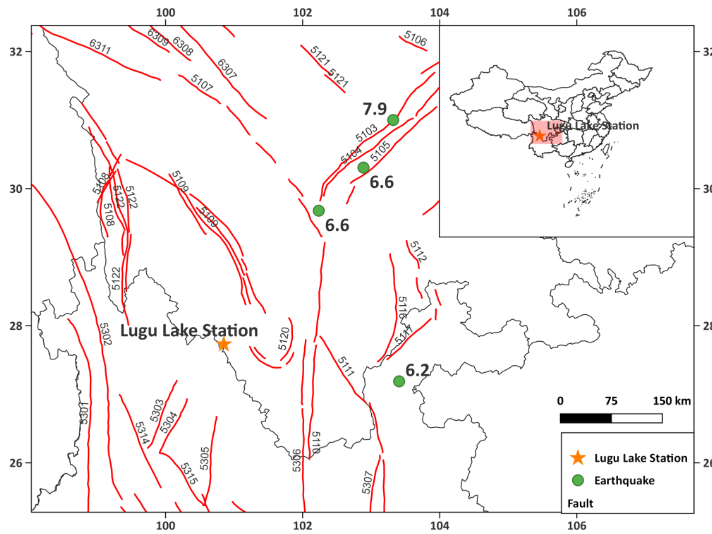

Figure 1. Distribution of earthquakes in and around the Lugu Lake Seismic Station

(5103, 5104, 5105: Longmenshan fault zone; 5110: Annin River fault zone; 5109: Litang-Derwu fault zone; 5122: Jinsha River fault zone)

The water level observation of the Lugu Lake station started in December 2007. The water level data have 1-min sampling intervals with a resolution of 1 mm. The precise time was determined using a Global Positioning System (GPS) or Simple Network Time Protocol (SNTP) to ensure temporal consistency with a resolution and accuracy of 5 s. The seismic events with magnitudes greater than 6.2 (Table 1) were selected for analysis within 500 km around the Lugu Lake station.

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Table 1. Seismic events with magnitudes greater than 6.2 within 500 km around the Lugu Lake Station

Identifier	Time	Latitude	Longitude	Mag (mw)	Distance (km)	Location
EQ1	2008-05-12 14:28	31.002	103.322	7.9	437	58 km W of Tianpeng, China
EQ2	2013-04-20 08:02	30.308	102.888	6.6	350	56 km WSW of Linqiong, China
EQ3	2014-08-03 16:30	27.1891	103.4086	6.2	258	33 km WSW of Zhaotong, China
EQ4	2022-09-05 12:52	29.6786	102.236	6.6	257	44 km SE of Kangding, China

2. Method

In order to calculate the tidal response parameters of the well water level more accurately, a low-pass filter with a cut-off frequency of 48h^{-1} is used to extract the trend of the well water level. Then, the low-frequency data is subtracted from the original data, and only the tidal components of the well water level is retained (Figure 2).

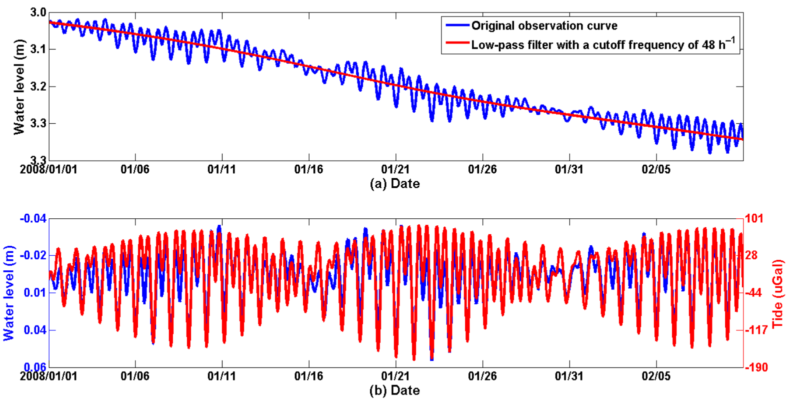

Figure 2. Tidal components of the well water level is retained

The t_tide tool provided by Pawlowicz et al. (2002) was used to calculate the magnitude and phase of each tidal sub-wave (Figure 3), which was carried out by comparing the groundwater level and theoretical solid gravity tide to make the

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magnitude and phase comparable in the time series. For example, for the M2 wave (period of 12.42 h), the magnitude and phase parameters of the groundwater level and the solid gravity tide were calculated separately using the t_tide tool and then according to Equation (1).

$$f = A_w / A_g$$
$$\varphi_d = \varphi_w - \varphi_g \qquad (1)$$

where f is the groundwater level tidal factor of the M2 wave, A_w and A_g are the groundwater level and gravity tidal oscillation amplitude in mm and uGal, respectively. φ_w and φ_g are the phases of groundwater level and M2 sub-wave of the gravity tidal wave, respectively; φ_d, the phase difference between the groundwater level and gravity tidal wave is greater than 0 to indicate a phase lead and less than 0 to indicate a phase lag.

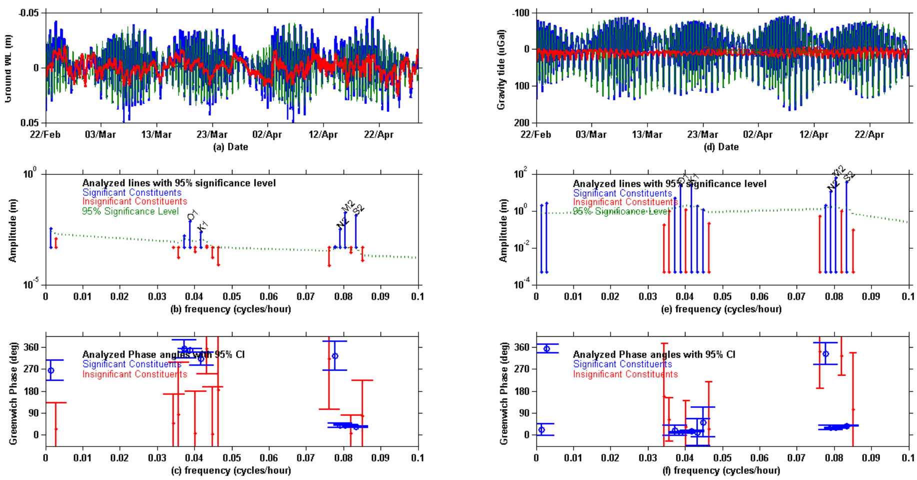

Figure 3. Tidal parameter calculations using the t_tide tool for the Lugu Lake Station groundwater level and theoretical gravity tides

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3. Results

The multi-year variability of water level is shown in Figure 4; the annual variation of the water level in the Lugu Lake well is approximately 1 m and a clear solid tide was recorded, that showed an annual variation pattern of high in winter and low in summer. The water level shows less disturbed, the data observed were stable and reliable, in addition to seasonal perturbations.

All four selected seismic events show significant coseismic responses, remarkably, the Wenchuan earthquake (Mw 7.9, 437 km) on May 12, 2008 caused a minor step increase in the water level of the well, the other three earthquakes caused significant step decline in the water level, and the magnitude of the step decline of the water level and of the earthquake are found to show a positive correlation.

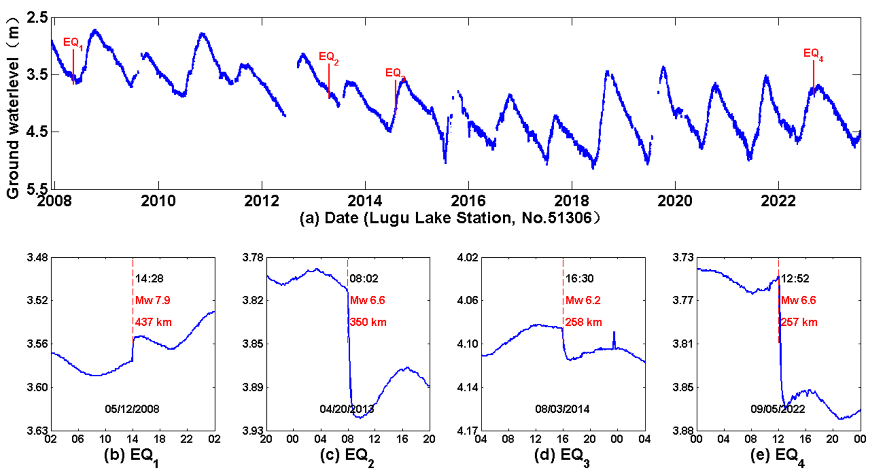

Figure 4. Multi-year variations of water level in the Lugu Lake station and co-seismic response to earthquakes

The used data was collected over a period of 60 days for each calculation, e.g.,

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the result for the data collected from February 21–April 20, 2008 is showed in Table 2.

Table 2. The results for the data collected from February 21–April 20, 2008

tide	Period (h)	Groundwater level demodulation				Gravitational tidal demodulation			
		amp	amp_err	pha	pha_err	amp	amp_err	pha	pha_err
MM	661.29	3.3	3	264.7	41.2	1.91	0.80	20.8	25.8
MSF	354.37	1.2	2	23.2	104.8	2.63	0.83	354.2	15.2
ALP1	29.07	0.5	1	48.1	101.5	0.18	1.15	157.9	213.3
2Q1	28.01	0.2	1	84.5	200.2	0.99	1.51	62.8	105.3
*Q1	26.87	1.6	1	352.4	35.4	4.77	1.52	19.6	17.6
*O1	25.82	7.2	1	346.3	8.5	25.16	1.56	9.4	3.3
NO1	24.83	0.3	1	6.4	166.6	1.20	1.71	32.5	99.5
*K1	23.93	2.4	1	311.6	28.3	27.94	1.68	14.8	3.5
J1	23.1	0.6	1	352.7	105.7	1.73	1.50	10.5	57.9
OO1	22.31	0.2	1	4.0	182.9	1.10	1.12	52.6	64.6
UPS1	21.58	0.1	0	185.6	205.8	0.20	0.74	24.7	193.6
EPS2	13.13	0.1	0	312.0	208.3	0.52	1.22	341.5	160.0
MU2	12.87	0.5	0	324.5	52.5	2.00	1.57	332.0	42.3
*N2	12.66	3.3	1	40.2	9.1	11.16	1.85	30.5	9.0
***M2**	**12.42**	**17.4**	**1**	**39.7**	**1.7**	**59.10**	**1.73**	**30.5**	**1.8**
L2	12.19	0.3	0	5.9	75.4	0.92	1.07	323.9	78.9
*S2	12	13.3	1	33.6	2.0	34.89	1.62	37.8	2.5
ETA2	11.75	0.1	0	78.9	133.8	0.09	0.74	104.4	221.8
MO3	8.39	0.1	0	19.9	168.4	0.21	0.08	71.4	20.6
M3	8.28	0.2	0	88.3	67.5	1.00	0.09	47.8	4.8
MK3	8.18	0.2	0	112.6	69.6	0.03	0.06	186.6	116.1
*SK3	7.99	0.3	0	236.8	35.5	0.04	0.06	246.9	94.7
MN4	6.27	0.1	0	36.5	54.8	0.02	0.02	112.6	41.8
M4	6.21	0.1	0	46.4	100.3	0.02	0.01	72.7	37.6
SN4	6.16	0.1	0	1.2	74.8	0.03	0.02	7.3	28.3
MS4	6.1	0.1	0	86.7	65.9	0.02	0.02	236.1	44.8
S4	6	0	0	246.9	119.7	0.03	0.01	118.4	28.9
2MK5	4.93	0	0	74.3	157.2	0.02	0.01	176.3	16.8
2SK5	4.8	0	0	35.2	156.1	0.02	0.01	220.7	20.0
2MN6	4.17	0	0	258.9	122.3	0.02	0.01	302.0	25.9
M6	4.14	0	0	206.7	161.9	0.01	0.01	174.6	31.6
2MS6	4.09	0.1	0	66.3	45.5	0.02	0.01	54.5	23.6
2SM6	4.05	0	0	275.0	89.4	0.01	0.01	232.5	39.7
3MK7	3.53	0	0	265.0	128.0	0.01	0.00	315.2	11.1
M8	3.11	0.1	0	36.9	48.7	0.01	0.00	357.6	3.4

Calculating the M2 wave tidal parameters for February 21-April 20, 2008, according to Equation (1):

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$$f = \frac{A_w}{A_g} = \frac{17.4mm}{59.10uGal} = 0.2944\ mm/uGal$$

$$\varphi_d = \varphi_w - \varphi_g = 39.7 - 30.5 = 9.2° = \frac{9.2}{360} * 12.42 * 60 \approx 19\ min$$

Following this procedure, the M2 fractional wave eigenvalues of the groundwater level for each of the four seismic events (Table 1) were calculated and the results are shown in Figure 5.

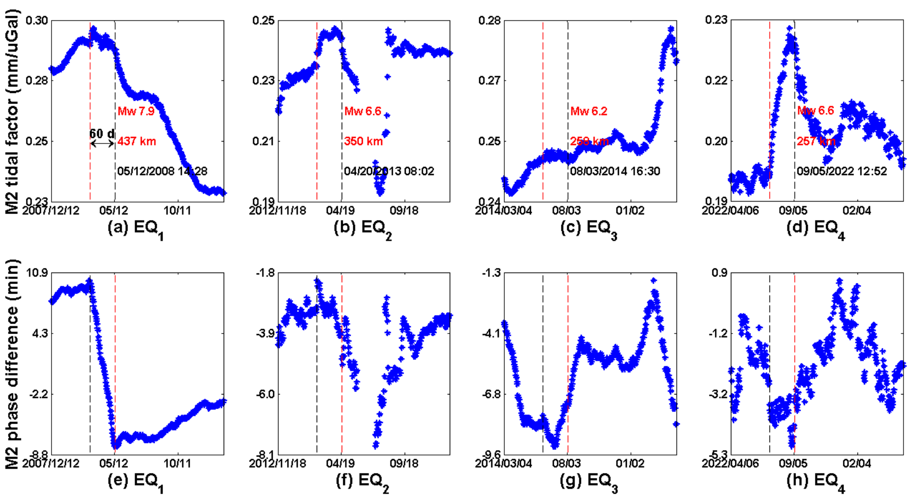

Figure 5. M2 fractional wave eigenvalues in four seismic events at the Lugu Lake Station well water level

The Wenchuan earthquake (05/12/2008, Mw 7.9) shows the greatest impact on the eigenvalues of the M2 sub-wave at Lugu Lake station. Its M2 wave tidal factor decreased from 0.28 mm/uGal prior to the earthquake to 0.23 mm/uGal, especially for the relative phase, which changed from an average phase lead of 10 min prior to the earthquake to an average phase lag of 9 min after the earthquake. In addition, the M2 sub-wave tidal factor size and phase lead size show an increasing trend prior to the

Wenchuan earthquake. It was difficult to affirm if the trend was anomalous prior to the Wenchuan earthquake due to the limited pre-earthquake observation data. The tidal factor size and relative phase changes were less evident in the other three earthquakes.

4. Discussion

The moon, the sun, and other celestial bodies exert gravitational force on Earth's mass points, which causes the volume of the Earth to change. The volume of the solid skeleton of the aquifer in the Earth's crust changes accordingly, resulting in changes in the aquifer's pressure head (pore pressure) and the consequent rise and fall of the water level in the well. For the ideal horizontal stratified pressurized aquifer model, the partial differential equation for the effect of solid tidal body strain on the pressure head of the pressurized aquifer can be derived from the theory of elasticity and theory of groundwater dynamics as follows:

$$\frac{\partial H}{\partial t} = \frac{K}{S_s}\nabla^2 H - \frac{1}{S_s}\frac{\partial \Theta}{\partial t} \qquad (2)$$

In the above equation, H is the pressure head within the aquifer, t is time, K is the permeability coefficient of the aquifer, S_s is the unit water storage coefficient of the aquifer, and Θ is the solid tidal body strain. Under the condition of no drainage, the simplified solution of equation (2) is:

$$H_n = \frac{-1}{S_s}\sum_i A_{ti}\cos(\omega_{ti} t - \varphi_{ti}) + H_0 \qquad (3)$$

In the above equation, A_{ti}, ω_{ti}, φ_{ti} are the amplitude, angular frequency, and initial phase of the ith harmonic of the solid tidal body strain at the moment t,

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respectively, and H_0 is the average pressure head of the aquifer. When there is a seepage influence between well-aquifer and only the case of solid tidal, an angular frequency(ω) harmonic is considered, and the equation solution can be changed to:

$$H_w = H_n + H_0 \cos(\omega t + \varphi_w + \Psi) \tag{4}$$

Where H_w is the pressure head of the well water column in the pressurized aquifer (groundwater level), φ_w is the phase angle of the groundwater level to the solid tide response. It can be seen that a certain independent sub-tidal wave in the groundwater level can be simplified to a sine-cosine function for calculation.

Regarding a well-aquifer model, the water barrier (impermeable layer) covering the top of the original aquifer is changed into a leakage aquifer, i.e., a semi-confined aquifer, which is a soil layer with poor permeability, and a head difference exists between the aquifer and adjacent aquifer. Although the permeability of the soil layer of the leaky aquifer is poor, under the condition that a head difference exists between the aquifer and neighboring aquifer, water seepage between the aquifer and leaky aquifer also occurs. Owing to the wide area of distribution, the total amount of water is considerable. Compared with the junction area between the aquifer, interface between the transgressive aquifer, and the borehole is negligible, i.e., the amount of water alternation between the transgressive aquifer and borehole is negligible.

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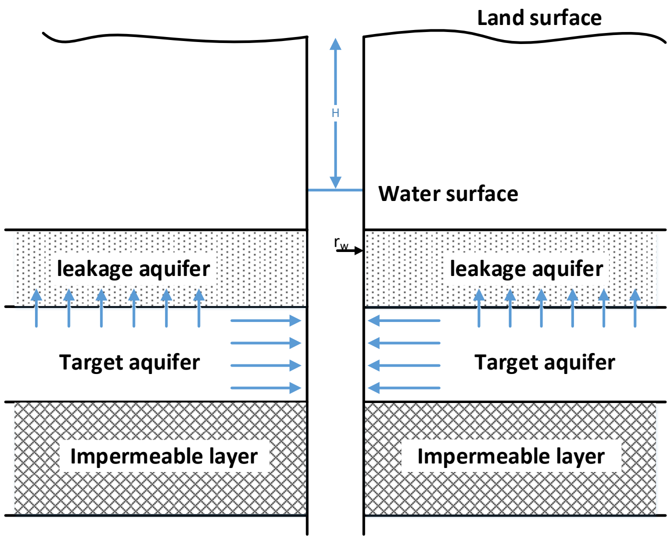

Figure 6. Well-Aquifer Modeling

A completely confined aquifer (Figure 6), without considering the friction and other factors, the water will directly squeeze into the borehole and its pressure will be transferred to the borehole without any loss, that raise the water level of the well. In a transgressive aquifer, the pressure within will be shared partially, affecting the efficiency of tidal response of the water level in the borehole. The efficiency of the tidal response of the groundwater level is affected by the presence of a transgressive aquifer. Compared to the simple one-dimensional well-aquifer structure, the water level in a borehole with a transgressive aquifer can be decomposed into two simple harmonic oscillations in the same direction and frequency.

$$x_1 = A_1 \cos(\omega t + \varphi_1)$$
$$x_2 = A_2 \cos(\omega t + \varphi_2) \qquad (5)$$

Where x_1 is the recharge of water from the ideal aquifer to the borehole and x_2

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is the loss of water from the aquifer to borehole owing to leakage to the semi-pressurized aquifer; the magnitude of the rise in the water level in the borehole can be expressed as $x = x_1 - x_2$:

$$\begin{aligned} x &= x_1 - x_2 \\ &= A_1 \cos(\omega t + \varphi_1) - A_2 \cos(\omega t + \varphi_2) \\ &= (A_1 \cos\varphi_1 \cos\omega t - A_1 \sin\varphi_1 \sin\omega t) - (A_2 \cos\varphi_2 \cos\omega t - A_2 \sin\varphi_2 \sin\omega t) \\ &= (A_1 \cos\varphi_1 - A_2 \cos\varphi_2)\cos\omega t - (A_1 \sin\varphi_1 - A_2 \sin\varphi_2)\sin\omega t \end{aligned}$$

taking $A\cos\varphi = A_1 \cos\varphi_1 - A_2 \cos\varphi_2$ and $A\sin\varphi = A_1 \sin\varphi_1 - A_2 \sin\varphi_2$

Then:

$$x = A\cos\varphi\cos\omega t - A\sin\varphi\sin\omega t = A\cos(\omega t + \varphi) \quad (6)$$

From Equation 6, it can be seen that the frequency of the synthesized simple harmonic continues in the same direction and its frequency remains unchanged. The amplitude and phase of the combined vibration are:

$$\begin{aligned} A &= \sqrt{(A\sin\varphi)^2 + (A\cos\varphi)^2} \\ &= \sqrt{(A_1 \sin\varphi_1 - A_2 \sin\varphi_2)^2 + (A_1 \cos\varphi_1 - A_2 \cos\varphi_2)^2} \\ &= \sqrt{A_1^2 + A_2^2 - 2A_1A_2\cos(\varphi_1 - \varphi_2)} \end{aligned} \quad (7)$$

$$\tan\varphi = \frac{A\sin\varphi}{A\cos\varphi} = \frac{A_1\sin\varphi_1 - A_2\sin\varphi_2}{A_1\cos\varphi_1 - A_2\cos\varphi_2} \quad (8)$$

Equation 8 shows that the phase of the combined vibration is related to the respective phases of the sub-vibrations and individual amplitude of the sub-vibration.

Here, we considered M_2 wave as an example, the simulations, procedure and

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performance are shown in Table 3.

Table 3. Calculations for simulating the amplitude and phase of water level oscillations in wells with transgressive aquifers

Steps	**Content**	**Illustrate**
1	$td = 1 \times cos(2\pi f\tau)$	Assuming the M2 sub-wave Earth solid tide, in which $f = 1.9324cpd$ (cpd - cycle per day)
2	$wl\_ideal = 1 \times cos(2\pi f\tau - 0.1\pi)$	Groundwater level vibration under an ideal pressurized aquifer structure, which is assumed to be in phase with the solid tide with a lag of 0.1π, indicating a lag of about 37 minutes
3	$wl\_leakage\_i = 1 \times cos(2\pi f\tau - 0.1 \times i \times \pi)$	Assuming that the transgressive aquifer causes the groundwater level to vibrate with an amplitude of 1, except that the phase is $0.1 \times i \times \pi$ $(i = 1,2,3, \ldots)$
4	$wl\_leakage\_j = 1 * j * \times cos(2\pi f\tau - 0.2 \times \pi)$	Assuming that the phase of the transgressive aquifer is fixed at a lag of 0.2π s, the amplitude takes the value of $1 * j$ $(j = 1，0.9，0.8 \ldots)$
5	$wl = wl\_ideal - wl\_leakage\_i$	Synthetic groundwater level

Considering the pressure of the target aquifer drives the recharge of the overflow aquifer, its phase will only be equal to or lag behind that of the target aquifer, and under the premise of keeping the amplitude of the overflow aquifer unchanged, $i = 1,2,3 \ldots$ were considered. The corresponding values of the phases are -0.1π ,-0.2π, -0.3π …, and the results of the calculations are as follows:

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i	Range	Phase	j	Range	Phase
1	0	——	1	0.313	-1.100
2	0.313	-1.100	0.9	0.313	-0.779
3	0.618	-0.942	0.8	0.344	-0.488
4	0.908	-0.785	0.7	0.398	-0.260
5	1.176	-0.628	0.6	0.468	-0.093
6	1.414	-0.471	0.5	0.547	0.028

Figure 7 shows i=1 indicates that the target aquifer pressure is all converted to the leaky aquifer; thus, the water level in the borehole will remain unchanged, which is only the ideal state. With the increase of the value of i, the phase lag in the leaky aquifer gets progressively larger, and the synthetic phase gets progressively closer to the theoretical value of the gravitational tidal phase. However, the phase is always in a "lead" state. Simultaneously, as the value of i increases, the synthesized amplitude increases in magnitude, and the magnitude may also exceeds the magnitude of the ideal pressurized aquifer structure.

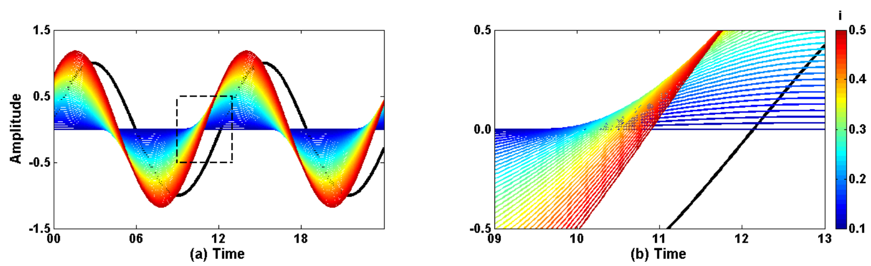

Figure 7. Water level changes in synthetic wells when the leaky aquifer amplitude is held constant and phase lag shows different values

Next, the phase value of the leaky aquifer is fixed (here, it is fixed to -0.2π,

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lagging behind the theoretical value of gravity tides by 0.2π). Its amplitude is changed by $j = 1，0.9，0.8 \ldots$, from the calculation results (Figure 8), the synthetic vibration phase lead becomes progressively smaller as the value of j decreases. Nevertheless, the synthetic vibration phases lead the theoretical solid-tide phases under the prerequisite of j>0.5, and lagging occurs only when the phase of synthetic vibration is j＜0.5; the synthetic vibration phase lags. Simultaneously, as the value of j decreases, the amplitude of the synthetic vibration progressively increases.

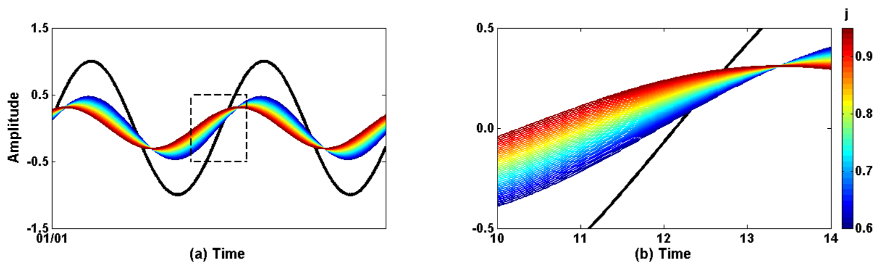

Figure 8. Water level changes in synthetic borehole when the phase lag of the leaky aquifer is held constant and the magnitude varies

The results shown in Figure 7&8 clearly show that closer the phase and amplitude of the leaky aquifer are to those of the ideal aquifer, the more the phase of its synthetic vibration lead to the theoretical solid gravity tide.

5. Conclusions

Based on the theoretical calculation our results show the large phase lag of the leaky aquifer, the closer the synthetic phase to the theoretical value of gravity tidal phase. But the phase always remains "phase lead"; simultaneously, the synthetic amplitude increased progressively, and the amplitude may even exceed that of the ideal pressurized aquifer structure. In addition, the smaller the oscillation amplitude of

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the leaky aquifer, the smaller the synthetic vibration phase lead. However, under the premise of $j>0.5$ (j is the amplitude ratio of the leaky aquifer relative to the ideal aquifer), the synthetic vibration phase lead was in excess to the theoretical solid tidal phase. The synthetic vibration phase lag occurred only when $j<=0.5$. Meanwhile, the synthetic vibration amplitude became progressively larger as the value of j decreased.

The Wenchuan earthquake caused the M2-wave tidal factor of the water level in the Lugu Lake Station well to decrease from 0.28 mm/uGal prior to the earthquake to 0.23 mm/uGal; the phase lead from an average of 10 min of pre-seismic overshooting to an average of 9 min of post-seismic lagging. The pre-earthquake phase leads over the theoretical gravity tide, indicates the existence of a leaky aquifer in the Lugu Lake well. After the earthquake, the phase changed from lead to lag, which can only be due to either the disappearance of the leaky aquifer or lagging of the synthetic vibrational phase because the amplitude ratio of the leaky aquifer relative to the ideal aquifer is $<=0.5$. The leaky aquifer, as an actual aquifer, cannot disappear because of the earthquake. However, the earthquake can only change the amplitude ratio of the leaky aquifer relative to the ideal aquifer.

The Wenchuan earthquake caused an increase in the permeability of the aquifer in the water wells of Lugu Lake station, and this increase may be due to the development of new fractures in the aquifer (Tokunaga, 1999; Zhang et al., 2019; Sun et al., 2015) that enhances the permeability owing to the scouring of the fracture water in the aquifer caused by the seismic wave (Yoshimi and Oh-Oka, 1975; Dobry et al., 1982; Vucetic, 1994; Hsu and Vucetic, 2004; Lai et al., 2004; Wang and Manga, 2010). Owing to the new fractures, the former shows a permanent increase in permeability. Simultaneously, the latter will accumulate over time and revert back to the original

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level in the aquifer because of the accumulation of groundwater minerals. From the effect of several earthquakes, except for the Wenchuan earthquake, which caused the groundwater level to step up, the subsequent earthquakes caused the groundwater level to step down. However, the Wenchuan earthquake changed the permeability of the Lugu Lake well aquifer, which did not return to the pre-earthquake level, in line with the permanent increase in permeability and development of new fissures. Furthermore, the other three earthquakes did not show a permanent change in permeability and development of new fissures.

The Wenchuan earthquake led to the generation of new fissures in the Lugu Lake, which led to the conduction of deep high-pressure water into the aquifer, resulting in a co-seismic response of step-up; the subsequent earthquakes did not generate new fissures but seismic waves only caused fissure water flushing that enhanced the permeability of the aquifer and a step-down in the water level of the borehole when boreholes were close to the discharge zone (He and Singh, 2018). The M2 fractional wave tidal factor size and phase lead size prior to the Wenchuan earthquake showing an increasing trend; however, the anomalous nature of this trend prior to the Wenchuan earthquake can not be affirmed due to the limited pre-earthquake observation data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Code/Data availability

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At present, data and code can only be submitted to reviewers in the form of attachments.

Author contribution

Anhua He carry out the design of the manuscript ideas, Yang Liu & Fan Zhang completed data collection and editing work, Haixia Sun completed partial code, Yanzhang Wang and Ramesh P. Singh review and improve the manuscript.

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