Research on Skempton's coefficient B based on the observation of groundwater of Changping station*

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Abstract Based on isotropic linear poroelastic theory and under the undrained condition, we summarize three equations connecting the Skempton's coefficient B with the groundwater level. After analysis, we propose a method to calculate the Skempton's coefficient B according to the relationship between water level and tidal strain. With this method we can get the value of B without the earthquake occurrence, which can provide the high frequency waves for research. Besides, we can also get the in-suit Skempton's coefficient B without the experiment of rock physics. In addition, we analyze the observed data of Changping station recorded in groundwater monitoring network (abv., GMN) before and after the Wenchuan $M_s8.0$ with this method, and find out there's a slight change of the value of B after the seismic waves passed by, which implies that the propagation of seismic waves may have brought some variations to the poroelastic medium of the well.

Key words: Skempton's coefficient B ; water level; tidal strain; atmospheric pressure; volumetric strain

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1 Introduction

Skempton's coefficient B is a significant pore-fluid parameter, which is defined as the ratio of the induced pore pressure to the change of stress loading under undrained condition (Skempton, 1954; Wang, 2000). The Skempton's coefficient B can also be explained by the compressibility of rock and pore fluid (Brown and Korrington, 1975; Bishop, 1966; Bruggeman et al, 1939). Generally, the value of B was measured via experiment of rock physics and was considered as a constant for a specific rock type (Rice and Cleary, 1976; Roeloffs and Rudnicki, 1984; Roeloffs, 1996). Recently, scientists calculated the value of B by using water level observation data as well as barometric pressure and volume strain in well confined aquifer system under the undrained condition (Chadha et al, 2008; Sil, 2006; Kano and Yanagidani, 2006; Yan et al, 2008).

Through measuring the value of B of sandstone, marble, and granite via experiment, Mesri et al (1976) found that for all four rock types, B is close to 1 at low effective pressure, but fell to values between 0.33 and

0.69 at effective pressures of 10 MPa. Green and Wang (1986) suggested that decreasing of B -value with increasing effective stress was probably related to crack closure and/or high-compressibility materials within the rock framework. Berryman (2003) found that the shear modulus G is a function of the Skempton's coefficient B . The above-mentioned results showed that the B -value can change with different stress state and/or the crack's open-closure state in a specific aquifer system.

In this paper, we summarize three equations calculating the Skempton's coefficient B based on linear poroelastic theory. We analyze those methods and find out the relationship between water level and tidal strain is the most reasonable one to get the value of B in a relatively stable state without the earthquake occurrence. With this method, we calculate the value of B both before and after the Wenchuan earthquake and find that the B -value is relatively stable and will change slightly (about 10%) after the earthquake happened. It implies the propagation of seismic waves may have brought about some influence on the characteristics of the well aquifer.

2 Poroelastic theory

Skempton's coefficient B is a significant pore-fluid

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parameter in poroelastic theory. Poroelastic material consists of an elastic matrix containing interconnected fluid saturated pores. Fluid saturated crust behaves as a poroelastic material to a very good approximation.

2.1 constitutive relation of poroelastic medium

Rice and Cleary (1976) summarized the following equations for a linearly elastic isotropic porous medium, which are the building blocks of poroelastic theory.

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)}p\delta_{ij}, \quad (1)$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}, \quad (2)$$

here $m - m_0$ is the fluid mass change, ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, δ_{ij} is the Kronecker delta function, G is the shear modulus, ρ is the density of the fluid, B is the Skempton's coefficient, p is the pore pressure, ν is the Poisson ratio and ν_u is the "undrained" Poisson's ratio. Rice and Cleary (1976) described equation (1) as a stress balance equation and equation (2) as a mass balance equation.

Under the undrained condition, the poroelastic effect on the crust can be obtained by putting $m - m_0 = 0$ in equation (2). Thus we obtain

$$P = -\frac{B\sigma_{kk}}{3} \quad \text{or} \quad \Delta p = -\frac{B\Delta\sigma_{kk}}{3}. \quad (3)$$

Equation (3) is under "undrained" condition and presents change of fluid pressure (ΔP) is proportional to the change of mean stress ($\Delta\sigma_{kk}$). This is the mechanism of water level changes for poroelastic material ($p = \rho gh$, where h is the water column height, g is the acceleration due to gravity and ρ is the density of water) (Sil, 2006).

2.2 Definition of Skempton's coefficient B

According to equation (3), Skempton's coefficient B can be qualitatively defined as under the "undrained" condition, B is the ratio of the induced pore pressure (p) to the change in mean stress ($\sigma_{kk}/3$) (a negative sign indicates compressive stress) (Wang, 2000). B governs the magnitude of water level changes due to an applied stress, as pore pressure is directly proportional to water level ($p = \rho gh$, where h is the water column height). The value of B is always between 0 and 1. When B is 1, the applied stress is completely transferred into changing pore pressure. That B equals to 0 indicates no change in pore pressure after applying the stress. When an aquifer is not confined, an applied stress can be easily transferred outside the aquifer system without increasing the

pore pressure. Thus a low value of B indicates a poorly confined aquifer system (Sil, 2006). Laboratory studies indicate the value of B depends upon the fluid saturated pore volume of the sample (Wang, 2000).

2.3 Relationship between water level and volumetric strain

Equation (3) can also be expressed in terms of volumetric strain (Roeloffs, 1996)

$$h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\varepsilon_{kk}. \quad (4)$$

Equation (4) shows that water level changes proportionally in a poroelastic material under the influence of an induced volumetric strain (ε_{kk}) (Sil, 2006).

2.4 Relationship between pore-pressure and atmospheric pressure

Apart from earthquake-induced water level changes, poroelastic theory can also explain typical fluctuations observed in continuously recorded water level data due to changes in atmospheric pressure and tidal strain. Since atmospheric pressure is unidirectional, in the z (vertical) direction, putting $\varepsilon_{xx} = \varepsilon_{yy} = 0$ and $m - m_0 = 0$ in equations (1) and (2) respectively, we can obtain the ratio between water level change and barometric pressure change as (Roeloffs, 1996)

$$\frac{\Delta h}{\Delta b} = \frac{B}{3\rho g} \frac{1+\nu_u}{1-\nu_u}, \quad (5)$$

here Δh is the change in water level and Δb is the change in pore pressure.

2.5 Relationship between pore-pressure and tidal strain

Tidal strain can also influence water level. The effect of tidal strain will be the same as described by equation (4). The relationship can be written as

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\Delta\varepsilon_t, \quad (6)$$

here Δh is the change in height of water level, and $\Delta\varepsilon_t$ is the corresponding tidal strain change (Sil, 2006).

3 Background of Changping station

Changping (Dong Sanqi) station locates in Changping county, Beijing city. The altitude is 38.8 m. It is about 1321 km away from Wenchuan. The geostructure cell of the site belongs to the cross area of Yiansan structure belt and Xihuaxia structure belt of North China. The regional structure locates in Laiguangying anticline at Beijing sunken area. The site locates at the cross area of NE Huangzhuang-Gaoliying fault, WNW

Nankou-Sunhe fault and NNE Babaoshan fault. The surface belongs to Quaternary system sediment layer. The structure activities are comprehensive in this area and it is a sensitive site for earthquake precursor observation (Fang, 1998).

Changping volume strain station is a substation of the Sacks comprehensive volume strain observation network at Capital Circle area. The depth of borehole for the volume strain gauge is 285 m. The stratum above 198 m at the site is Quaternary system loosen sediments layer. It is made up of clay, sand clay and thin gravel. The lower stratum is Sinian system resembling limestone. The instrument in the borehole is Sacks-Eyertson drilled strain gauge. The sensitivity is set as 10–11/mV. The measurement accuracy is 10–9/mV. The data can record clear Earth tides and are stable.

The observations of water level and volume strain are in the same borehole at Changping station. The sensor of volume strain is located at the bottom of the well, while the sensor of water level is located at several me-

ters below water surface. This well is made up of two aquifers. The upper part above 198 m belongs to pore water. It is supplied mostly by precipitation and surface water infiltration. The lower part is cranny karst water of carbonate rock. The cranny and water are rich. The water is confined. Barometric pressure data are observed in Changping station via barometer once a day. Tidal strain data are calculated via Mapsis software (Wu et al, 2006; Zhang, 2005; Yan et al, 2008).

4 Analysis on three methodologies based on the observation of groundwater

It seems that with the observation data of water level, atmospheric pressure, volumetric strain and tidal strain, we can use the three methods to calculate the Skempton's coefficient B from those three equations (4), (5), (6).

We can see the correlativity between the water level and the other factors of Changping station in Figure 1.

Figure 1 Correlation coefficient of water level with solid tide, barometric pressure and volume strain for Changping station from January 1, 2008 to May 11, 2008 in the frequency-domain (Lai et al, 2009).

4.1 Undrained condition

Since the definition of the Skempton's coefficient B is based on the undrained condition, we should discuss this issue firstly. In fact, the “darined” or “undrained” condition depends on the specific circumstances. Under the “undrained” condition, the change of the effective

stress can only be attributed to the change of the total stress since there is no fluid flowing out, which may be caused by incidents such as constructing buildings or dams in the crust, the periodic effect of the earthquake in the crust, the effect of the solid tide in the aquifer, and the burials in the geologic basin and so on (Narasimhan

and Kanehiro, 1980). Generally, sudden stress in the crust by an earthquake in a relatively short time can be considered as an “undrained” condition (Roeloffs, 1996; Wang, 2000). Similarly, the “drained” condition is reached after relatively long duration, when the pore fluid flow equalizes the fluid pressure gradients caused by the earthquake (Sil, 2006). And for the effect of solid tide, when the wavelength of the tidal strain is much larger than the size of the aquifer, we can suppose the aquifer system is undrained (Huang, 2008). The thickness of the aquifer in Changping station is less than 285 m, and the wavelength of the M2 wave is about 2 406 329 km ($\lambda = \omega \times r \times T$, $\omega = 1.4 \times 10^{-4}/s$ is the angular frequency of M2 wave, $r = 384\,400$ km is the distance from the earth to the moon, $T = 44\,714$ s is the period of the M2 wave), which is much larger than the thickness of the aquifer system. Besides, the wavelengths of other waves of the tidal strain will also be much larger than the size of the radius of the Earth. Thus, the effect of the solid tide in the crust can meet with the undrained condition.

4.2 Skempton's coefficient B calculated according to the relationship between water level and tidal strain

As shown in Figure 1, the correlation coefficient of the water level and the tidal strain approaches 1 when the period T comes to about 700 to 800 min, which means a good correlativity between them. As discussed above, this relationship can meet with the undrained condition. Since that, we distill the frequency of the M2 wave (the period of M2 is 745.236 min equals to 12.42 h) from the water level and the tidal strain to calculate the Skempton's coefficient B . Besides, the M2 wave is hardly influenced by atmospheric pressure, which is another reason to calculate with it.

4.3 Skempton's coefficient B calculated according to the relationship between water level and atmospheric pressure

From Figure 1 we can also see that for the relationship between the water level and the atmospheric pressure, when the period comes to about 9 000 minutes (150 h), the correlation coefficient is close to 1. However, this long period may expand the limitation of the “short time” of the “undrained” condition.

Earlier, several authors got the Skempton's coefficient B from the relationship between atmospheric pressure and water level (Sil, 2006; Chadha et al, 2008). The merit of this method is that it does not refer to the supposed shear modulus G . However, they have not proven whether the effect of the atmospheric pressure in the crust can meet with the undrained condition.

We have supposed the effect of the atmospheric pressure in the crust could meet with the undrained condition, and tried to get the value of B from this relationship. But through the data processing, we found the phase lag is too large (more than 10 h), and is unstable. It is always changing with the change of the data length no matter whether the earthquake occurs. Since that, the value of B gotten from this relationship is not reliable. The effect of the atmospheric pressure in the crust may not satisfy the undrained condition.

4.4 Skempton's coefficient B calculated according to the relationship between water level and volume strain

If we want to use volume strain and water level to calculate the value of B , we can use the high frequency part (the frequency of the earthquake waves). Yan et al (2008) got the Skempton's coefficient B of Changping station with this method based on the data of the Sumatra earthquake, and the correlativity between the water level and the volume strain in the high frequency domain at the time of the Sumatra earthquake is fairly well. They achieved that the value of B in Changping station is 0.804.

The duration of the earthquake waves is extraordinary short, we can just use this method to calculate the Skempton's coefficient B when the earthquake happened, but can hardly use it to calculate the value of B before or after the earthquake. What's more, as Figure 1 shows, the correlativity between water level and volume strain in the high frequency domain at the time of the Wenchuan earthquake is unsatisfactory. Figure 2 shows the correlativity is not ideal clearly. Thus, if we still want to use this relationship to calculate the value of B , we may meet with some difficulty.

Figure 2 Response of the water level and the volume strain of Changping station to the Wenchuan $M_s 8.0$ earthquake on May 12, 2008.

The water level and volume strain are removed from linear trend. 0 is the time when the Wenchuan earthquake happened.

From the analysis above, we can see that the calculation of the Skempton's coefficient B according to the relationship between water level and tidal strain is the most reasonable method in a relatively stable state without the earthquake occurrence.

Figure 3 Raw hourly water level data and tidal strain data (a); Water level and the tidal strain after removing linear trend (b); Frequency domain analysis of the water level and the tidal strain (c); Distilled frequency of M2 wave from the water level and the tidal strain (d).

Suggest $\rho=1\,000\text{ kg/m}^3$, $g=9.8\text{ m/s}^2$, $\nu_u=0.29$ and suppose $G=3\text{ GPa}$.

From equation (6) we can obtain

$$B = -\frac{3\rho g(1-2\nu_u)}{2G(1+\nu_u)} \frac{\Delta h}{\Delta \varepsilon_i}. \quad (7)$$

We distill the frequency of M2 wave from the water level and the tidal strain by the strategy of band-pass filtering (the frequency of M2 wave is $0.080\,511\,4\text{ h}^{-1}$, both the water level and the tidal strain have high energy in this frequency domain) (Figure 3). Dispose the distilled frequency parts of M2 wave by IFFT, and adjust their phase (normalize their amplitudes, and put them into one picture, we can see there are no phase lags be-

5 Methodology for data processing

We mainly use the band-pass filtering based on the correlation coefficient of the water level and the tidal strain (Figure 1) (Lai et al, 2009) and the least square inversion to get the value of B from equation (6). We choose the pre-earthquake part (from May 1, 2008 to May 11, 2008) to calculate B (Figure 3).

tween the water level and the tidal strain obviously) (Figure 4), through the least square fit and put the result into equation (7), finally we can achieve the pre-earthquake Skempton's coefficient $B=0.850\,5$ (In order to remove the boundary effects, after the band-pass filtering we choose the processed data from May 2, 2008 to May 10, 2008 according to the data sequence.)

6 Analysis on the results

As calculated above, the value of B of Changping station is $0.850\,5$, it is approximately identical with 0.804 , which is calculated through the relationship between the water level and the volume strain with the high frequency domain data when the Sumatra earth-

quake happened (Yan et al, 2008).

Figure 4 Distilled frequency parts of M2 wave from the water level and the tidal strain disposed by IFFT (a); M2 wave of the water level and the tidal strain in one picture after normalizing their amplitudes (b).

If we choose different lengths of time to calculate the Skempton's coefficient B in a relatively stable state, the results will be almost the same (Figure 5). There is no phase-lag between the water level and the tidal strain for the duration of this time span. The choice of the data length depends on the stability of the data. Large amount of missing data or the occurrences of earthquake will limit the data length.

Figure 5 Continuous value of B obtained from the relationship between the water level and the tidal strain (From May 2, 2008 to May 10, 2008). We get one value every 24 hours from the hourly data.

7 Discussion

We get the value of B through the relationship between water level and tidal strain in this paper, and the result is reasonable compared with the result achieved by Yan et al (2008). However, there's still something needs to be discussed.

7.1 Viscous effect

Rice and Cleary's linear constitutive equations are the reformulation of Biot's linear poroelastic constitutive equations, and Biot's theory is based on the generalized Darcy's law, which ignores the inertial and viscous effects. Generally, only for those widely opened stones with well developed fissures and fast flow fluids,

the viscous effect is important and can not be neglected; while for that slowly flow fluids saturate the aquifer, we can ignore the viscous effect (Bodvarsson, 1970). Thus, the neglect of the inertial and viscous effects may not cause obvious impact on the result of the value of B in Changping station.

7.2 Undrained condition

In reality, the discussed "undrained" condition can hardly last for a long time. As long as the fluid flow exists, the undrained condition will disrupt and be replaced by the drained condition soon.

7.3 Mechanism of the change of the value of B before and after the earthquake

We have also applied the method based on the relationship between the water level and the tidal strain to the post-earthquake part from May 14, 2008 to May 22, 2008, and the post-earthquake value of B is 0.9412.

We can compare the pre- and the post-earthquake results according to Figure 6.

Generally, the Skempton's coefficient B is relatively stable, while it may alter slightly (about 10%) after the earthquake happened (Figure 6).

Figure 6 Continuous value of B obtained from the relationship between the water level and the tidal strain. Pre-earthquake: May 2, 2008 to May 10, 2008; Post-earthquake: May 14, 2008 to May 22, 2008. We get one value every 24 hours from the hourly data.

According to rock physics, the Skempton's coefficient B can be understood as the compressibility parameters of rock, fluid and the micro-crack as the following equation (Bishop, 1966)

$$B = \frac{\beta_d - \beta_u}{\beta_d - \beta_u + \phi(\beta_f - \beta_u)}. \quad (8)$$

In equation (8), ϕ is the porosity, β_f is the pore fluid compressibility, β_d and β_u are the “drained” and “undrained” bulk volume compressibility parameters, respectively. After the propagation of seismic waves, the cracks of the medium may have opened or closed, and the density of micro-crack in rocks and the pore-pressure may change, thus the porosity and the compressibility parameters are likely to vary, which would probably lead to the slight change of the value of B .

7.4 Shear modulus

Since each well has its specific geology, it's difficult to decide the shear modulus for the wells. What's more, the shear modulus G is found to be the function of the Skempton's coefficient B (Berryman, 2004). In this paper we just suppose $G=3$ GPa (to be the same with the value of G which is used by Yan et al, 2008), and assume that it will not change before and after the earthquake. However, we can not determine the in-suit shear modulus accurately. The value of B will decrease with increase of the value of G , according to the equation (6). Since that, the difference of the value of B between the pre-earthquake and the post-earthquake will also decrease with increase of the value of G .

8 Conclusions

We have proposed a method to calculate the Skempton's coefficient B with the records of water level and tidal strain from this study. With this method we can get the value of B without the earthquake occurrence, which can provide the high frequency waves for research. And we can also get the in-suit Skempton's coefficient B without the experiment of rock physics. From the analysis we know the relationship between water level and atmospheric pressure may not meet with the undrained condition, and probably can not be used to calculate the Skempton's coefficient B .

From our research we can see the value of B is relatively stable and will have a slight (about 10%) change after the Wenchuan $M_s 8.0$ happened. It implies the propagation of seismic waves may have brought in some influence on the characteristics of the well aquifer. Besides, the supposed undrained condition, the ignored

inertial and viscous effects and the supposed unchangeable shear modulus G may also cause some impact on the value of B . Other influence factors and explanations remain to be confirmed by further studies.

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