

Effect of Fracture Compressibility on Fluid-in-Place Calculation of Chingshui Geothermal Reservoir, Taiwan

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ABSTRACT

Naturally existing tritium in groundwater was applied as a tracer for dating the age of Chingshui geothermal water. The residence time (or, age) was determined at 15.2 years using the plug-flow model with tritium data. The rate of natural recharge for Chingshui geothermal reservoir can be estimated from the production history from 1981 to 1993. Fluid-in-place can then be calculated from the residence time (or, age) and recharge rate. Alternatively, fluid-in-place can be calculated using the porosity-thickness product obtained from well interference tests. This paper shows that ignoring the effect of fracture compressibility can lead to overestimating the porosity-thickness product and fluid-in-place of Chingshui geothermal reservoir, a stress-sensitive naturally fractured reservoir.

1. INTRODUCTION

Taiwan is located on a convergent and compression boundary between the Philippine Sea and Eurasian Plates. The collision of these two tectonic plates explains the presence of numerous geothermal areas and frequent earthquakes. The Chingshui geothermal field is located at northeastern Taiwan. The tritium concentration of geothermal water was measured in 1982, 1984 and 1985 (Chen et al., 1989). Chen et al. (1989) and Cheng et al. (1989) determined the residence time of Chingshui geothermal water using tritium data. Chang and Ramey (1979) and Fan et al. (2005) analyzed the results of the 1979 interference test in the Chingshui geothermal reservoir and obtained the porosity-thickness product.

Fluid-in-place can be calculated from the residence time (or, age) and recharge rate. Alternatively, fluid-in-place can be calculated using the porosity-thickness product obtained from well interference tests. The objectives of this study are: (1) to compare the estimates of fluid-in-place of the Chingshui geothermal reservoir using the above two methods, and (2) to evaluate the effect of fracture compressibility on fluid-in-place calculation for the Chingshui geothermal reservoir.

2. GEOLOGY

The Chingshui geothermal area is an area of hot springs situated along Chingshui River, approximately 13 km southwest of Ilan, Taiwan, as shown in Figure 1. Geologically, this area is composed of dark-gray and black slates, namely the Miocene Lushan Formation. Lushan Formation can be lithologically divided into three members: the Chingshuihu Member, the Jentse Member, and the Kulu Member. In general, the Jentse Member is composed mainly of metasandstones intercalated by slates, while the Chingshuihu and Kulu Members consist mostly of slates. Figure 2 shows that there are numerous thrust faults near the Chingshui geothermal area. The most important ones are the Tashi, Hsiaoananao and Hanhsi faults, which essentially trend NE-SW parallel to the bedding (Hsiao and Chiang, 1979). Along the Chingshui River, there is the normal, N-S striking Chingshuihsi fault.

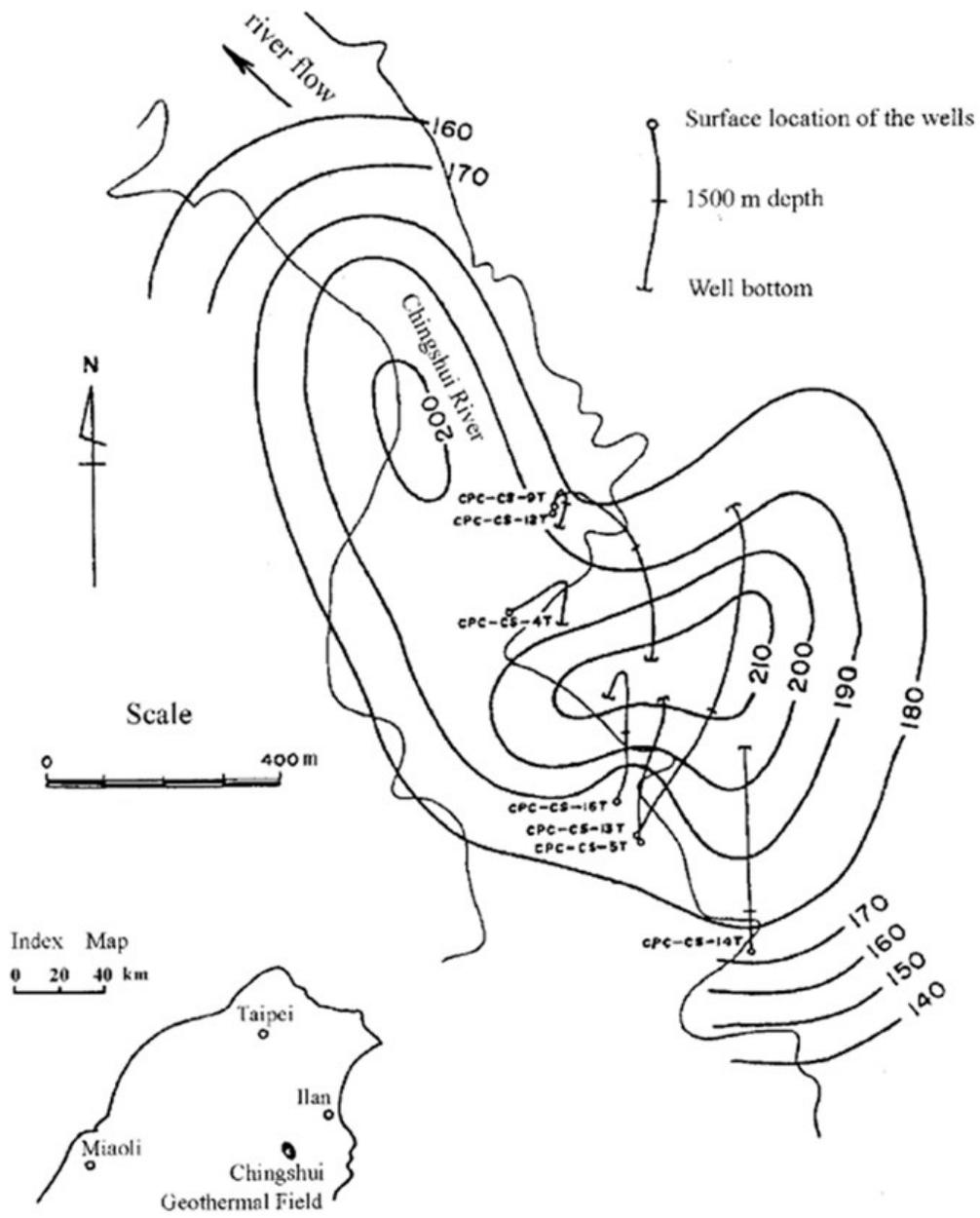


Figure 1: Location of the wells and the isotherms of presumed formation temperature for 1500 m depth in the Chingshui geothermal area (Chang and Ramey, 1979).

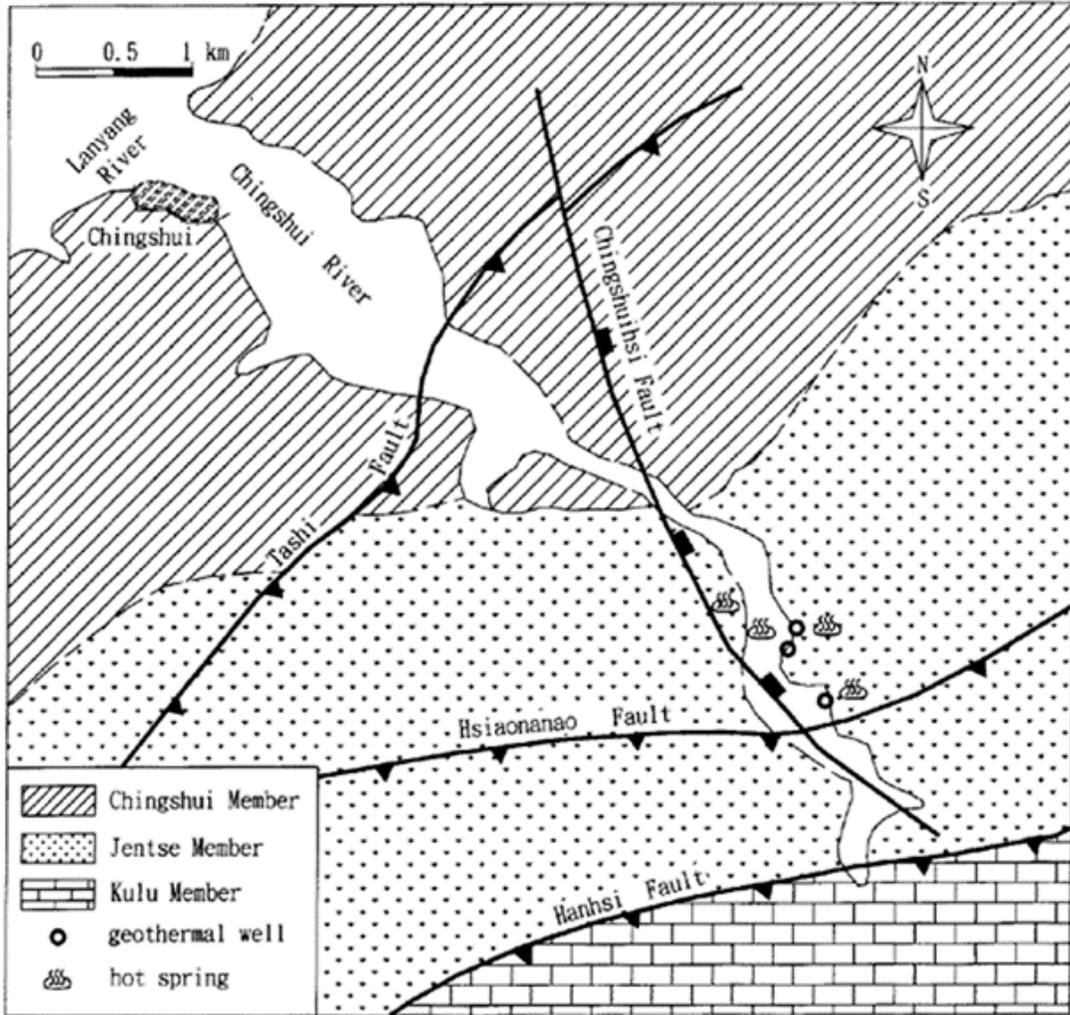


Figure 2: Geological map of the Chingshui geothermal area showing the Chingshuihu, Jentse, and Kulu members of the Miocene Lushan Formation. Triangles and rectangles indicate the up-dipped sides of the reverse faults and the direction of dip of the normal fault, respectively (from Fan et al., 2005).

There is clear evidence that the geothermal reservoir is fracture dominated. The porosity and permeability of the slates are poor. Faults, joints, and other extensive fractures provide the conduits for the geothermal fluid flow. Predominant joints, which are almost aligned perpendicular to the strike of the strata, are found densely developed in the sandy Jentse Member. The most prominent set of joints strikes northwest and dips between 65° and 80° to the southwest (Tseng, 1978). The trend of the Chingshui River is almost parallel to that of the joints. In the geothermal field, there are numerous hot springs and fumaroles along the river. Figure 1 also shows both surface and bottom-hole locations of the geothermal wells. The area of the Chingshui geothermal reservoir is about 2 km^2 .

3. RESIDENCE TIME AND NATRURAL RECHARGE

Tritium is intrinsically a natural radioactive nuclide with a half-life of 12.43 years and emits 18.6 keV (maximum) beta radiation. Kaufman and Libby (1954) first recognized the potential for dating groundwater with cosmogenic tritium. As geogenic tritium in most groundwater is negligible, measurable tritium in groundwater virtually signifies meteoric-water recharge.

Dating of groundwater by decay of tritium assumes that the tritium input into a groundwater is known and that the residual tritium measured in a groundwater is the result of decay alone. The tritium concentration of geothermal water was measured in 1982, 1984 and 1985 in Chingshui geothermal field (Chen et al., 1989). Table 1 shows the measured data. A close examination of Table 1 indicates that the tritium concentration does not correlate with the location of wells. Instead, the tritium concentration appears to decrease with the sampling date. Table 1 also shows the average concentrations of tritium measured for the Chingshui geothermal water at various sampling dates.

Table 1: Tritium concentration in Chingshui geothermal water (Cheng et al. 2010).

Well number	Tritium concentration (pCi / L)							
	5-82	10-82	1-84	5-84	8-84	11-84	3-85	5-85
4T	116	72	35	29	55	27	27	18
5T	103	62	33	49	58	27	21	39
9T	112	71	44		23	54	30	49
12T	91	78	28		16	36		
13T	116	101		38		18	30	47
14T		98	27	30		32	17	
16T	113	56	30	18	61	55	33	14
Mean	109	77	33	33	43	36	26	33
Std. Dev.	10	17	6	12	21	14	6	16

* 1 $pCi / L = 0.3088$ TU (1 TU = 3.238 pCi / L)

Using IAEA worldwide data, the tritium concentration in precipitation of Hong Kong (114.2° E, 22.3° N) is close to Taiwan (121° E, 23.5° N) in location. Figure 3 shows the least- squares regressed line for the tritium concentration in precipitation of Hong Kong. The date April 1, 1963 was set for time zero when the peak concentration of tritium was observed. The regressed equations for the tritium concentration in precipitation at Hong Kong are as follows (Cheng et al., 2010).

from 4 – 1 – 1963 to 1 – 1 – 1978

$$\log C_{HK} = -5 \times 10^{-12} T^3 + 9 \times 10^{-8} T^2 - 0.0006 T + 2.405 \quad (1)$$

from 1 – 1 – 1978 on

$$\log C_{HK} = -7 \times 10^{-5} T + 1.3795 \quad (2)$$

where C_{HK} is the regressed concentration of tritium in precipitation at Hong Kong, TU; and T is the time since April 1, 1963, day. A tritium unit (TU) is the equivalent of 1 tritium atom in 10^{18} atoms of hydrogen. One TU is equivalent to 3.238 pCi/L of water.

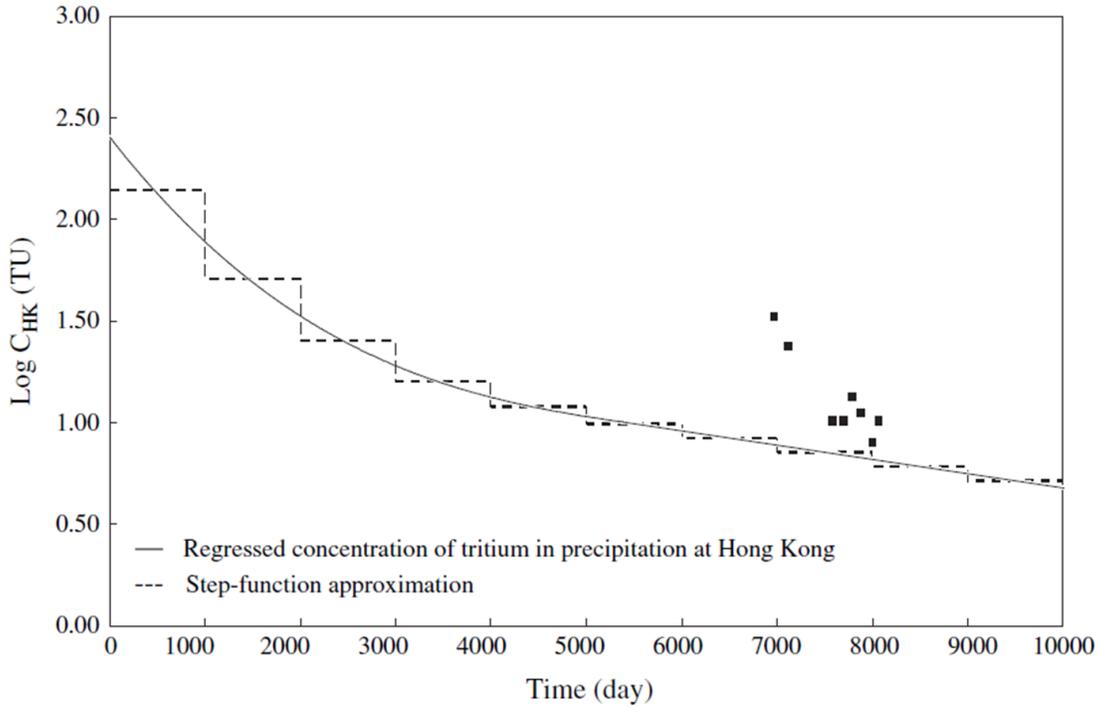


Figure 3: Variation of tritium content in precipitation at Hong Kong. Time zero is set on April 1, 1963. The solid squares denote measured tritium content in Chingshui geothermal water (Cheng et al. 2010).

In addition, Figure 3 shows a big difference between the average concentrations of tritium measured for Chingshui geothermal water at various sampling dates and those reported in the precipitation at Hong Kong. The big difference is caused by the decay of tritium since the infiltration of precipitations, or, the residence-time (or, age) of Chingshui geothermal water. The residence-time of Chingshui geothermal water can be determined by minimizing the difference between the corrected concentrations of tritium and those reported in the precipitations of Hong Kong as follows.

The piston flow model was used to determine the residence time of Chingshui geothermal water. The piston flow model assumes that the concentration of tritium changes only due to the radioactive decay. Decay corrections for the measured concentrations of tritium due to the residence-time of Chingshui geothermal water can be made as follows.

$$C_{model} = C_{HK} \times e^{(-0.693 \Delta t)/(12.43 \times 365)} \quad (3)$$

where C_{model} is the predicted concentration of tritium in Chingshui geothermal water using the plug flow model, TU; C_{HK} is the regressed concentration of tritium in precipitation at Hong Kong, TU; and Δt is the residence-time of Chingshui geothermal water, day. Notice that the time used in the decay correction for tritium is also the residence-time of Chingshui geothermal water. Figure 4 compares tritium content measured for Chingshui geothermal water with that predicted using the plug flow model with residence time as parameter. The residence-time (or, age) of Chingshui geothermal water can be best estimated at 15.2 year using the plug flow model (Cheng et al., 2010).

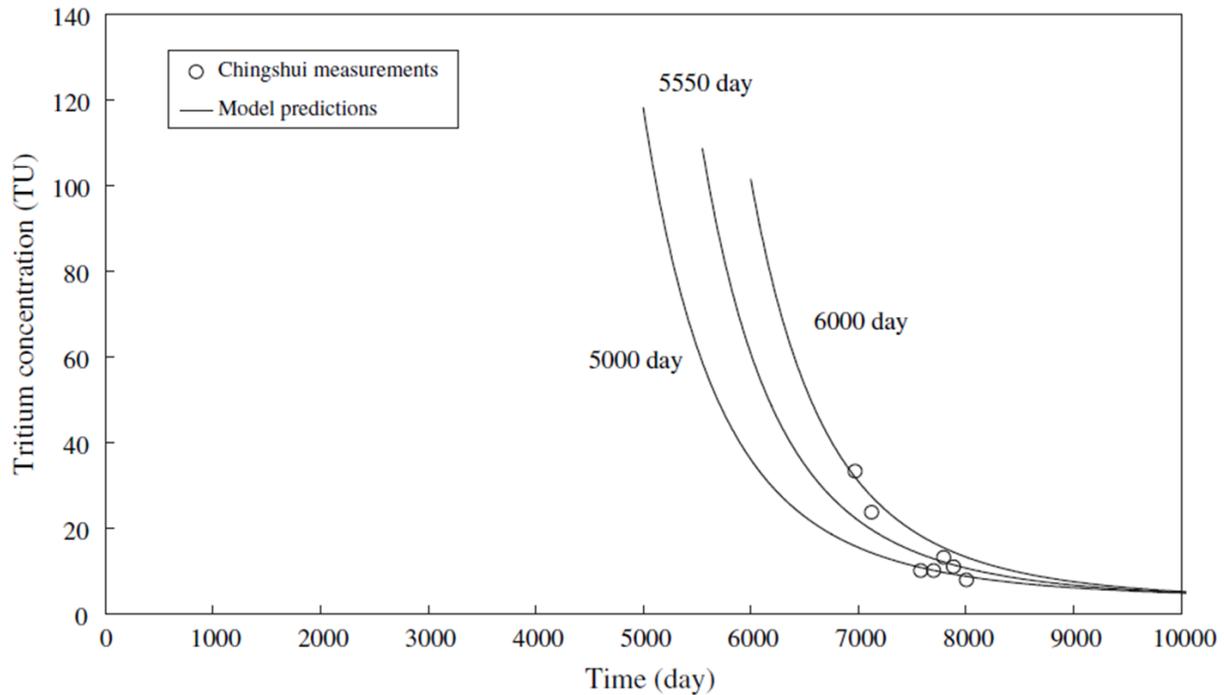


Figure 4: Comparison of tritium content measured for Chingshui geothermal water with that predicted using the plug flow model with residence time as parameter. Time zero is set on April 1, 1963 (Cheng et al. 2010).

Figure 5 shows the production history of Chingshui geothermal field from 1981 to 1993. There was no re-injection of spent geothermal fluids. The field deliverability of geothermal fluids declined sharply from 300×10^3 kg / hour in 1981 to 100×10^3 kg / hour in 1984. The field deliverability stabilized at about 50×10^3 kg / hour from 1991 to 1993. The natural recharge for Chingshui geothermal water can reasonably be estimated between 100×10^3 kg / hour and 50×10^3 kg / hour. A conservative recharge-rate for Chingshui geothermal water can be estimated at about 50×10^3 kg / hour, or, 5.2×10^5 m³ / year. An optimistic recharge-rate for Chingshui geothermal water can be estimated at about 100×10^3 kg / hour, or, 10.4×10^5 m³ / year.

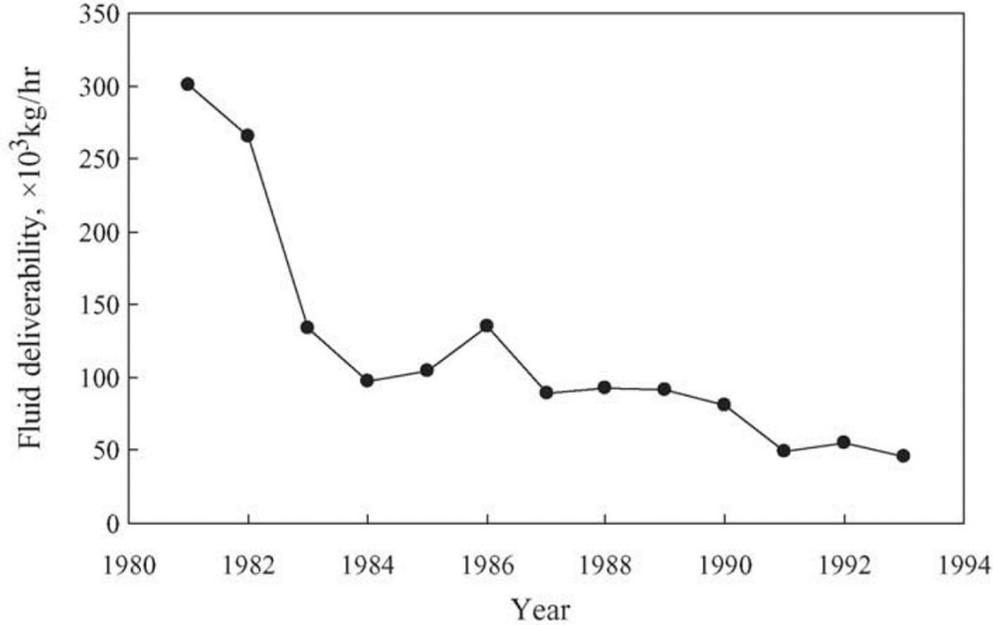


Figure 5: Production history of Chingshui geothermal field from 1981 to 1993 (Fan et al. 2005).

4. ESTIMATION OF FLUID-IN-PLACE USING RESIDENCE TIME

The fluid-in-place (*FIP*) for Chingshui geothermal reservoir can be calculated with the residence-time of Chingshui geothermal water and the natural recharge rate using the following equation.

$$FIP = R (\Delta t) \quad (4)$$

where *FIP* is the fluid-in-place for Chingshui geothermal reservoir, m^3 ; *R* is the natural recharge for Chingshui geothermal reservoir, $m^3/year$; and Δt is the residence-time of Chingshui geothermal water, *year*.

Given a conservative estimate of recharge rate, $R = 5.2 * 10^5 m^3/year$ and $\Delta t = 15.2 year$, the fluid-in-place (*FIP*) for Chingshui geothermal reservoir can be estimated as $7.9 * 10^6 m^3$. For an optimistic estimate of recharge rate, $R = 10.4 * 10^5 m^3/year$ and $\Delta t = 15.2 year$, the fluid-in-place (*FIP*) for Chingshui geothermal reservoir can be estimated as $15.8 * 10^6 m^3$.

5. ESTIMATION OF FLUID-IN-PLACE USING POROSITY-THICKNESS PRODUCT

Production in the liquid-dominated Chingshui geothermal field, Taiwan is largely from a fractured zone in the Jentse Member of the Miocene Lushan Formation. An interference test was conducted for the initial assessment of the field in 1979 (Chang and Ramey, 1979). During the 1979 test, well 16T was the production well, and pressure responses were observed in wells 4T, 5T, 9T, 12T, 13T, and 14T. Figure 1 shows both surface and bottom-hole locations of these wells. As an example, well 4T will be used to illustrate the volumetric method using the porosity-thickness product from interference testing.

The most commonly-used analytical solution for interpreting an interference test is Theis solution (Theis, 1935) and the line source solution (van Everdingen and Hurst, 1949) in groundwater and petroleum engineering, respectively. The line source solution assumes a constant production rate case in an infinite-acting, isotropic, reservoir. Chang and Ramey (1979) and Fan et al. (2005) used the line source solution to analyze the 1979 interference-test data.

Figure 6 shows the match of the pressure versus time data with the line source solution for well 4T. As shown in Table 2, the porosity–total compressibility–thickness product ($\phi c_t h$) of $6.04 * 10^{-2} m - (kg/cm^2)^{-1}$ can be calculated from the time match. Given a total compressibility (C_t), the porosity–thickness product (ϕh) can be determined.

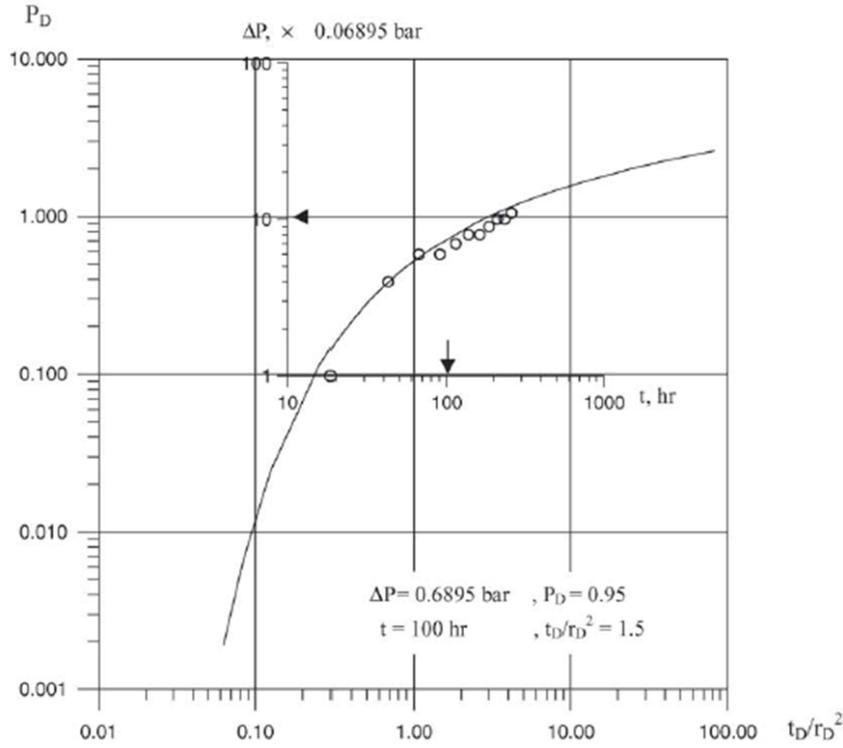


Figure 6: Type-curve match for well 4T using the line source solution (Fan et al. 2005).

Table 2: Porosity-total compressibility-thickness product ($\phi C_t h$) obtained from type-curve matching of interference test data for well 4T at Chingshui, Taiwan.

Match point	
$\Delta p = 0.7031 \text{ kg/cm}^2 = 10 \text{ psi}$	$p_D = 0.95$
$t = 100 \text{ hrs}$	$t_D/r_D^2 = 1.5$
Distance, m	175
$\frac{kh}{\mu}$, Darcy-meter cp	77
$\phi C_t h, \text{ m} - (\text{kg/cm}^2)^{-1}$	$6.04 * 10^{-2}$

$$q = 105 \text{ tons/hr}; v_{sc} = 1.08 \text{ cm}^3/\text{g}$$

$$B = 1.1 \text{ reservoir volume/surface volume}$$

The total compressibility (C_t) consists of geothermal-water compressibility (C_w) and fracture compressibility (C_f). Fan et al. (2005) assumed that fracture compressibility (C_f) is negligible and obtained the porosity-thickness product (ϕh) as follows.

$$C_t = C_w = 1.42 \times 10^{-4} (\text{kg/cm}^2)^{-1}$$

$$\phi h = 425 \text{ m}$$

The fluid-in-place can be calculated by a volumetric method using the following equation.

$$FIP = \phi h A \quad (5)$$

where FIP is fluid-in-place, m^3 ; ϕh is porosity-thickness product, m ; and A is area, m^2 . Based on the isotherms map (Figure 1), the area of the Chingshui geothermal reservoir is estimated to be around 2 km^2 . The fluid-in-place for Chingshui geothermal reservoir can be calculated as follows.

$$FIP = (425 \text{ m}) \times (2 \times 10^6 \text{ m}^2) = 8.5 \times 10^8 \text{ m}^3$$

The fluid-in-place for Chingshui geothermal reservoir estimated from porosity-thickness product is about two orders of magnitude greater than that estimated from residence time. One possible reason for the significant difference in the above estimates can be due to ignoring the effect of fracture compressibility. The Chingshui geothermal reservoir is a stress-sensitive naturally fractured reservoir.

6. CONCLUSIONS

1. Fracture compressibility can play an important role in the calculation of fluid-in-place in stress-sensitive naturally fractured reservoirs.
2. Ignoring the effect of fracture compressibility can lead to overestimating the porosity-thickness product and fluid-in-place of Chingshui geothermal reservoir.

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