

Numerical Evaluation for Production Performance of Chingshui Geothermal Reservoir, Taiwan

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ABSTRACT

In 1981 a 3MWe capacity geothermal power plant was built at Chingshui, which is one of the representatives of geothermal development in Taiwan. However, the power plant was decommissioned in 1993 due to continued decline in production. Although some geothermal exploration and field production had been exercised in the past, the production potential of Chingshui geothermal reservoir is still not well understood. The purpose of this study is aimed to investigate production performance of the power plant through numerical modeling approaches. Computer simulation for the natural state was undertaken for understanding the reservoir fluid flow process at the site. Based on the natural state model, we further built a production model to simulate the production history during 1981-1993. The model was calibrated with production data, but it was impossible to match real exploitation conditions without considering the formation scaling. Based on the constant pressure production scenario, we adjusted permeability surrounding the wellbores varying with time to simulate the effect of scaling phenomena. The calibrated model shows good production history matching. From the modeling exercises, we may conclude that the decline in production of the power plant was mainly caused by formation scaling, but there was also a limited impact due to availability of water resources.

1. INTRODUCTION

The Chingshui geothermal field is located in the northeast portion of Taiwan, approximately 20 km southwest of Lotung town. In the area, several high-temperature hot springs along the Chingshui River have been noted historically. This fact, and exploration activities that are discussed below, led to the construction of the Chingshui geothermal power plant in 1981. The installed capacity of the plant was 3 MW. Unfortunately, by 1993, the pilot power plant was decommissioned due to continued decline in production to uneconomic levels. Although geothermal reservoir exploration and field tests had been exercised in the past, the production performance of Chingshui geothermal reservoir is still not well understood. There are several hypotheses for the failure: special characteristics of the Chingshui geothermal reservoir not being adequately understood at the time, and/or inappropriate power generator being used and severe scaling of the pipelines (Hwang, 2010). Many engineers and researchers believe that the most important reason for the production capacity drop is carbonate scaling in the reservoir (Lin, et al., 2011; Lu et al., 2012). However, it is also believed that the production decline is due to the limitation of available water resources in the area. The purpose of this study is aimed at building a geothermal reservoir model to investigate the reservoir fluid flow process at the site and validate a particular hypothesis regarding reservoir failure. Specific details of the study are given below. Since reactivation of the plant is being contemplated, it is critical that we thoroughly understand reasons for drop in production and the maximum potential for production.

A number of studies have been conducted to characterize the Chingshui geothermal reservoir. A reconnaissance survey of this site was performed by the Industrial Technology Research Institute (ITRI) from 1973 to 1975. Further exploration was subsequently conducted by the Chinese Petroleum Corporation (CPC) from 1976 to 1980 (Tong, et al., 2008). Dozens of deep exploration and production wells were drilled along a 6-km bank of the Chingshui stream. In addition, numerical simulations and tracer tests were performed to investigate natural recharge of the reservoir (Fan, et al. 2006; Cheng, et al. 2010). Fan et al. (2006) combined the use of both tracer and interference tests to evaluate the natural recharge of Chingshui geothermal reservoir. Their estimations for mean residence time and natural annual recharge for the Chingshui geothermal reservoir are 15 years and $1.3 \times 10^7 \text{ m}^3/\text{year}$, respectively. In addition, they analyzed the interference test results for determining total fluid in place, which is about $2 \times 10^8 \text{ m}^3$. However, Cheng et al. (2010) obtained a much smaller natural recharge value for the reservoir by analyzing naturally existing tritium in groundwater. Their calculated natural recharge rates for Chingshui geothermal reservoir were $5.0 \times 10^3 \text{ m}^3/\text{year}$ and $6.7 \times 10^5 \text{ m}^3/\text{year}$ with a plug flow and dispersive model, respectively, and the corresponding groundwater residence times estimated by the two models were 15.2 and 11.3 years. All these calculations were based on limited data and simple models with high uncertainty.

Well skin effects of the tested wells at Chingshui geothermal field were investigated to quantify formation damage or reservoir clogging through buildup tests and radon measurements (Lin et al., 2011, Chen et al, 2011). Based on the observation of radon behavior during the flow tests of well IC-09 and a high skin factor ($S=78.5$) determined from a pressure test, Lin et al. (2011) believed formation damage resulted from carbonate scale in the skin zone. They estimated that reservoir permeability and the altered permeability of skin zone are approximately 1.06 md and 0.066 md, respectively. Similar conclusions were also reached by Chen et al. (2011). At the depth 600 m to 800 m of a production well drilled into the reservoir of slate host rocks, fractures, veins and open cracks filled up with calcite or aragonite minerals were observed (Lu et al, 2012). Surveys on outcrops show that there are many quartz veins occurring in slate formation, but few or no calcite veins. These observations strongly suggest formation scaling rather than carbonate precipitation inside the wells of the Chingshui geothermal field (Lu et al, 2012).

Numerical simulation is an effective approach for characterizing geothermal reservoirs and for assessing and predicting the reservoir response to planned development. Simulation has been used successfully in different geothermal reservoirs (O'Sullivan et al., 2009; Mottaghy et al., 2011; Romagnoli et al., 2010). As mentioned, the main purpose of this study is to investigate the reasons

of production decline of the Chingshui Geothermal plant through numerical simulations. An earlier version of the model, used for evaluation of different production scenarios, has been reported by Lee et al. (2013). In this study, a large-scale refined grid model was constructed for assessing the responses of the reservoir system under different production conditions and the influence of formation scaling on the well productions. The model was first calibrated by adjustment of the inflow rate from the bottom boundary until a good match was obtained with the natural state condition. Inclusion of CO₂ in the model, as observed in the field, has shown further improvement in simulation results. The calibrated model was then used to simulate the production history during 1981-1993. With the model, we intend to investigate the impact of availability of water resources on the production well performance. Moreover, the influence of formation scaling on well production was modeled through reduction of permeabilities at the skin zone surrounding the production wells. Simulation results support the hypothesis that the production failure of the Chingshui Geothermal plant is mainly due to the formation scaling, but also in some point by the limitations of the groundwater resource. With the development of refined grid model, we are able to calculate the amount of total geothermal resource in place, optimize the design of reinjection and production schemes, investigate approaches for preventing formation scaling, and further re-evaluate the feasibility of resuming commercial exploitation of the Chingshui geothermal system.

2. MODELING APPROACHES

A reliable model needs to be constructed before it can be used for prediction. A good model should be able to duplicate the reservoir natural (initial) state, to match the production history, and to correctly calculate responses of the reservoir to the production history. Approaches for building the three-dimensional (3D) Chingshui geothermal reservoir model are compiled as follows.

2.1 Conceptual Model

Chingshui area is in the metamorphic terrain. The reservoir is within the Lushan Formation of Miocene age. The Lushan Formation lithologically includes the Jentse, Chingshuihu, and Kulu Members. The Chingshui geothermal field is located on a monocline structure, which is cut internally by numerous thrust faults that are lightly curved (Hsiao and Chiang, 1979). In the geothermal field, three most important faults, including the G fault, the Xiaonanao fault and Chingshuihsu fault, are distributed (Fig. 1a). Well-developed fractures in these faults are observed. The best developed fractures in the slates are found near the most convex part of the Xiaonanao fault along the Chingshui River (Chen et al., 2011). Evidence shows that the geothermal reservoir is fracture dominated. However, due to the poor porosity and permeability of the slates, faults, joints, and other extensive fractures actually provide the conduits for the geothermal fluid flow. Geothermal production at Chingshui is largely from a fracture zone in the steeply dipping Jentse Member, which is composed mainly of metasandstones intercalated by slates (Hsiao and Chiang, 1979).

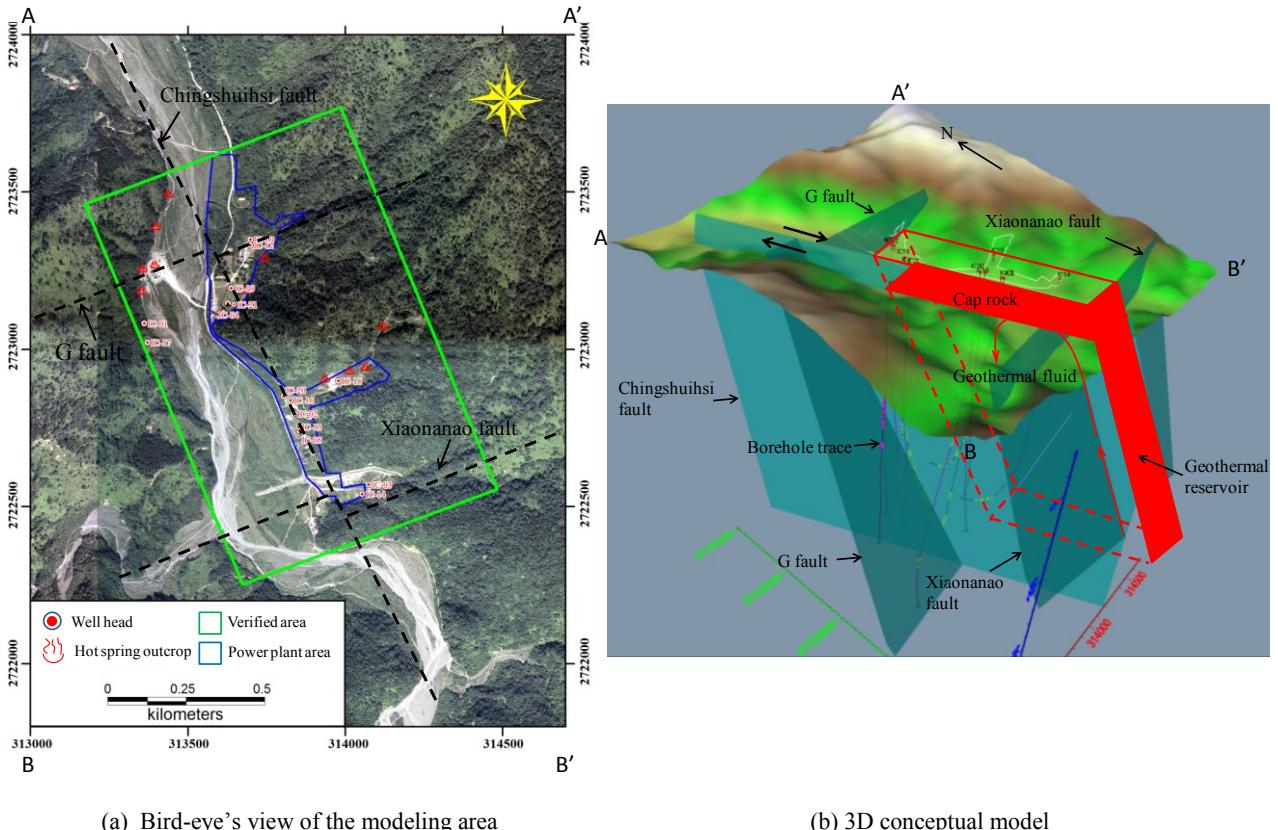


Figure 1: The conceptual model of the Chingshui geothermal reservoir (modified from Tong et al., 2008)

It is clear that the flow system of the geothermal reservoir is controlled mainly by the three faults. Fan et al (2005) confirmed that the flow regime in the reservoir is predominantly linear by reanalyzing the results of a multiple-well interference test performed in

1979. The geothermal reservoir is clustered with seepage zones. The seepage zones are confined in an area 260 m in width, N21°W, and dip 80° to the NE (Tong et al., 2008) which are in general corresponding to the distribution of the Chingshuihs fault.

Based on extensive geophysical exploration results together with knowledge of the geology in the Chingshui area, Tong et al. (2008) created a conceptual model for the Chingshui geothermal reservoir. The geothermal reservoir, with a NW-SE trend and about 1.5 km in length, is associated with the fracture zone of the Chingshuihs fault and is bounded by the G-fault and the Xiaonanao fault in the north and south, respectively (Figure 1a). The conceptual model for this study was modified from Tong's work (Figure 1b) by extending their range further north and south to include several additional exploration wells. Spatial distribution of the three faults is fully considered. The Chingshuihs fault runs NW-SE with a dip angle of 83.35° to the East. Both the G fault and Xiaonanao fault run almost perpendicular to the Chingshuihs fault, and dip 70° to the South (see Figure 1b).

2.2 Model Design

Figure 2 shows the grid structure of the 3D Chingshui geothermal reservoir model. Based on hydrogeology conditions at the site and the potential influence range of production, a model area of 3250m×4800m was selected, which covers the three faults, all production wells, and most exploration wells. Spatial distribution of those faults was fully considered in design of the grid. In vertical, the model includes a range from land surface to the elevation of -2000m. A grid size of 100m×100m in plan was selected for discretization. Refined grids of 10m×50m and 50m×50m were used at the fault zones and around several key wells for catching the rapid pressure change at near these areas. The thickness of the blocks in the top layer is varied to follow the topography of the modeling region. The model grid consists of 9905 columns divided into 43 layers with a total of 425,915 gridblocks and 1.27 million connections.

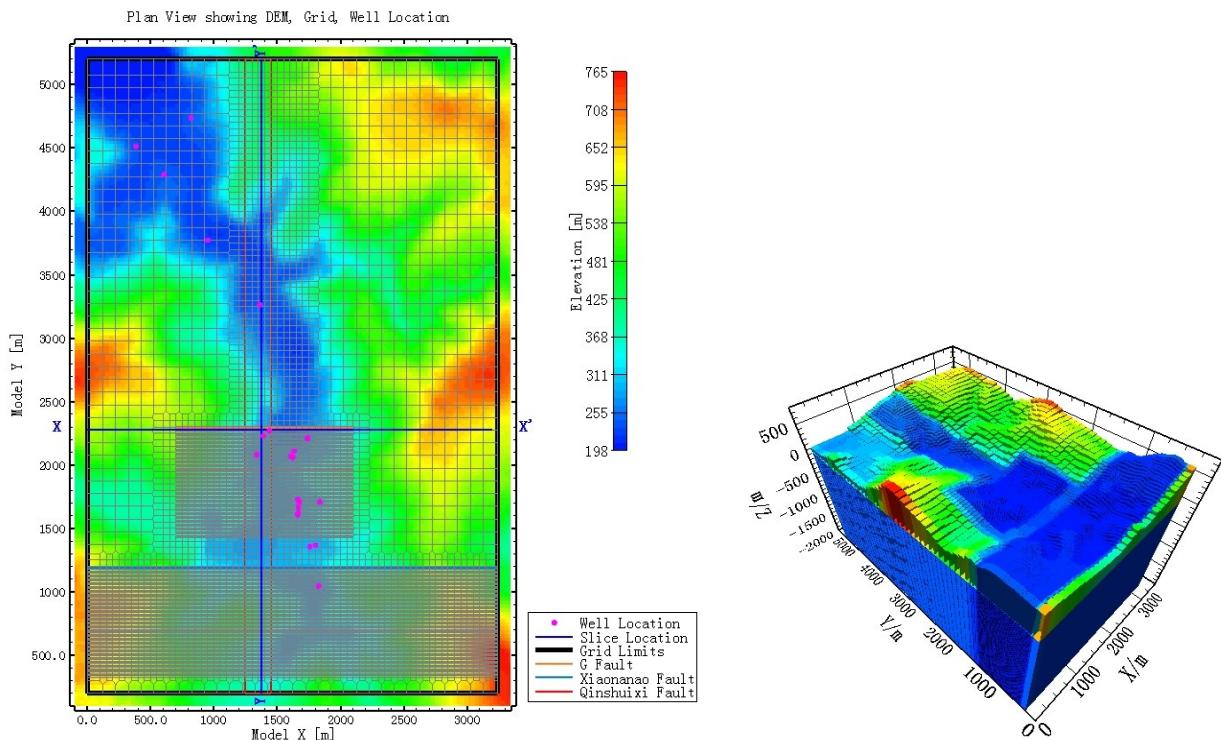


Figure 2: The space discretization of Chingshui geothermal model in plan and three-dimensional views

Table 1: Parameters of Chingshui geothermal reservoir model (Lee et al. 2012)

Rock type	Porosity	Permeability $k_{xy}(\text{m}^2)$	Permeability $k_z(\text{m}^2)$	Thermal properties
LOW	0.01	0.5^{-15}	0.5^{-15}	Heat source: 0.18 W/m ² Rock thermal conductivity: 3.0 W/m ² ° C
MID	0.05	5^{-15}	5^{-15}	
HIG	0.10	2.5^{-14}	2.5^{-14}	

With respect to hydrologic properties, tests in exploration wells indicate that the modeling domain can be divided roughly into three zones: the western side of the Chingshui River and south of the Xiaonanao fault (low permeability zone), the three faults (high permeability zone), and the eastern side of the mountain area (medium permeability zone). Rock hydraulic and geothermal properties for the three zones were summarized by Lee et al. (2012). Model parameters for the current study are modified from Lee's work (Table 1). Different rock properties around the heat source at the bottom boundary and surrounding the wells are determined through model calibration.

Heat and mass transfer at the top of the model is treated as the first type boundary. Atmospheric conditions with constant mean-annual temperature of 20°C are maintained at the top surface. This boundary condition allows water exchange between the model and land surface. Due to positive fluid pressures underground, significant water or moist air flowing back into the model domain from the atmosphere is not likely to happen. Heat can be lost by conduction to the atmosphere and by convection through water flowing to the top surface. Four sides of the model domain are treated as no-flow boundaries for both heat and fluid. By considering the low permeability of slate and model domain size, it is reasonable to assume that the influence of peripheral boundaries on production in the reservoir can be neglected. The bottom of the model is treated as the second-type boundary. A constant heat flow of 0.18W/m² is applied at the whole bottom boundary (Lee et al., 2012) and fluid recharges at a total rate of 12 kg/s (3.78×10^5 T/yr) with temperature of 260°C at the faults along bottom boundary. The recharge rate is determined by model calibration (see section below) with measurement temperature data in the wells, which is about 75% of the lower amount of natural recharge rate estimated by Cheng et al. (2010). It was observed that the groundwater in the reservoir contains significant amount of CO₂. Better match between model calculation and field measurement can be obtained if the recharged fluid consisting of 3% CO₂ is applied.

Simulation for Chingshui geothermal reservoir needs to consider multiphase fluid flow with components of water, CO₂, and heat. The EOS2 module of the TOUGH2 code (Pruess, 1998) was developed for such a simulation. TOUGH2 is a general-purpose reservoir simulator capable of simulating non-isothermal flows of multi-component, multi-phase fluids in porous and fractured media. For the large-scale simulations, the parallel version of TOUGH2 code, TOUGH2-MP (Zhang, et al., 2008), was selected. TOUGH2-MP was designed for computationally efficient parallel simulation by taking the advantage of modern multiple CPU/cores computer system. The EOS2 module describes fluid properties in CO₂-rich geothermal reservoirs, which may contain CO₂ mass fractions ranging from a few percent to occasionally 80 % or more (Atkinson et al., 1980). The module accounts for non-ideal behavior of gaseous CO₂, and dissolution of CO₂ in the aqueous phase with heat of solution effects.

2.3 Natural State Simulations and Model Calibration

Model predictions need to start from an accurate initial state (initial condition). The initial condition represents the known state of geothermal reservoir at a certain moment. It is common to choose the natural state as the system initial condition and this is because the natural state is relatively easy to determine. The natural state of underground flow system is assumed at steady-state, which represents a balance of fluid flow and energy entering and leaving the system. By giving the model boundary conditions, the steady-state (or natural state) of the model can be determined by running the simulation for a long time period. By calibrating the model, a more accurate natural state can be obtained. Chingshui geothermal reservoir model was calibrated by slightly adjusting the heat source flux at the bottom boundary and repeating simulations until a good match between model results and field measurements was obtained. The simulated temperatures were compared against measured temperatures in 16 wells. Figure 3 shows the comparison of 8 typical wells. By comparing to the simulation results of previous models (Lee et al. 2012), we can find that the current refined grid model with the consideration of CO₂ component in the simulation can significantly improve the model prediction for the natural state.

Further calibration has been done through the comparison of simulated and measured surface outflows of heat and mass. The permeabilities along the faults at bottom boundary, surrounding wells and several zones were also calibrated to achieve a satisfactory match. Figure 4 shows the simulated temperature distribution of the reservoir in natural state. As shown, high temperature distributes along the faults. A significant temperature gradient between the faults and surrounding slates can be observed. Figure 5 shows simulated CO₂ mass fraction distribution in a model vertical cross-section. The simulation results indicate the three faults are key factors controlling the system natural state.

Figure 6 shows the simulated distribution of outflow flux at the land surface. The high flux zone clearly corresponds to the river meander. The simulation results are in good agreement with the observations at the site. Hot springs are observed along the river bed or the river bank, especially at the southern bank of the Chingshui River extending for a range of 300 m in length. Note the temperature of the springs is between 60-99°C. It is obvious that the flux distribution is mainly controlled by Chingshui fault and G fault.

The calibrated steady-state model shows that the total fluid in the reservoir is about 1.23×10^9 m³, and the total recharge rate to the model is 4.03×10^5 m³/year. The model calculated total fluid in place is about six times higher than result of previous study by Fan et al. (2006), and the total recharge rate is about 81% of the estimation for total recharge rate to the geothermal reservoir by Cheng et al. (2010). The mean residence time of water in the reservoir, calculated from model, is much longer than previous studies.

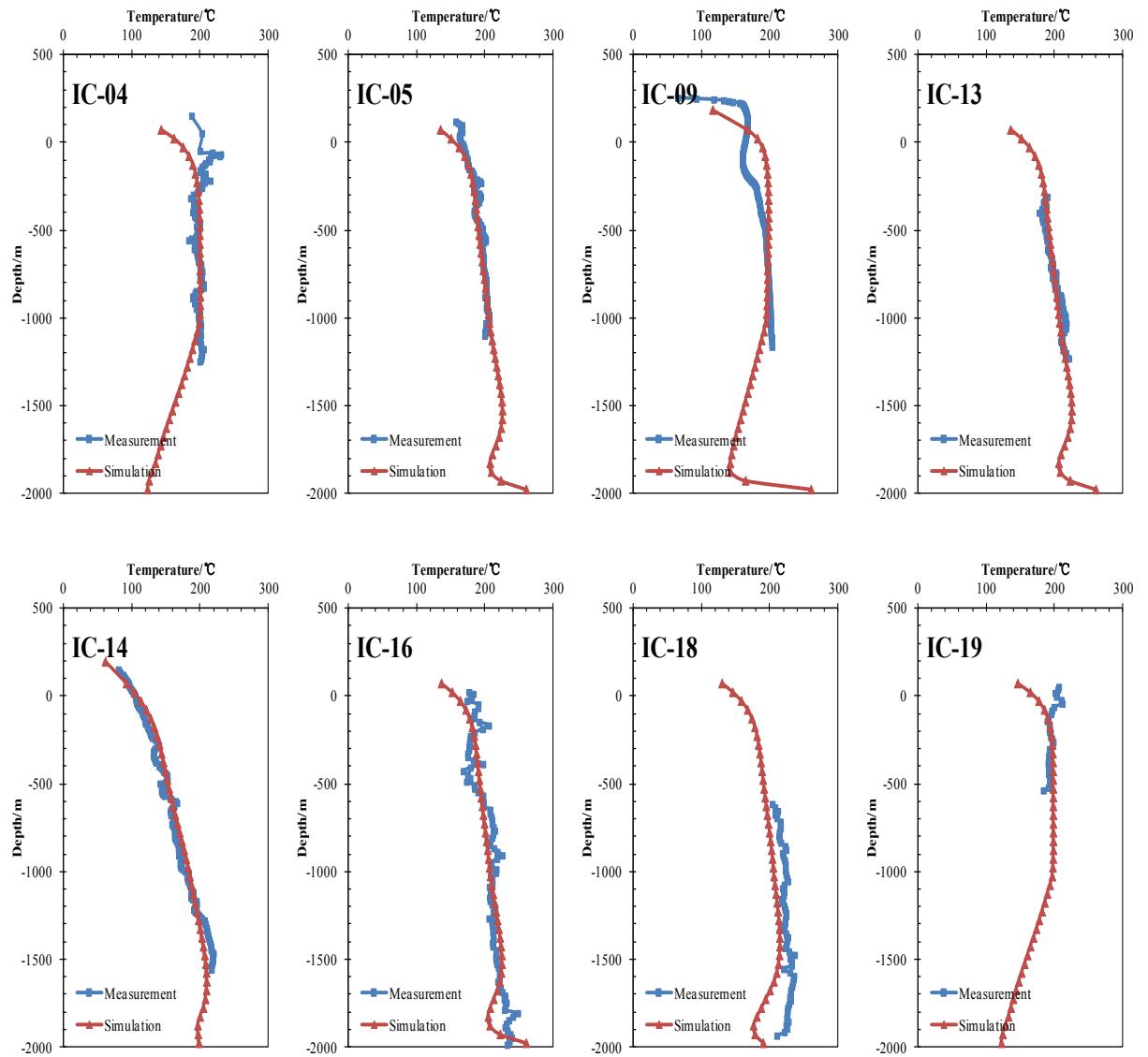


Figure 3: Comparison of well measured with simulated temperature in natural state

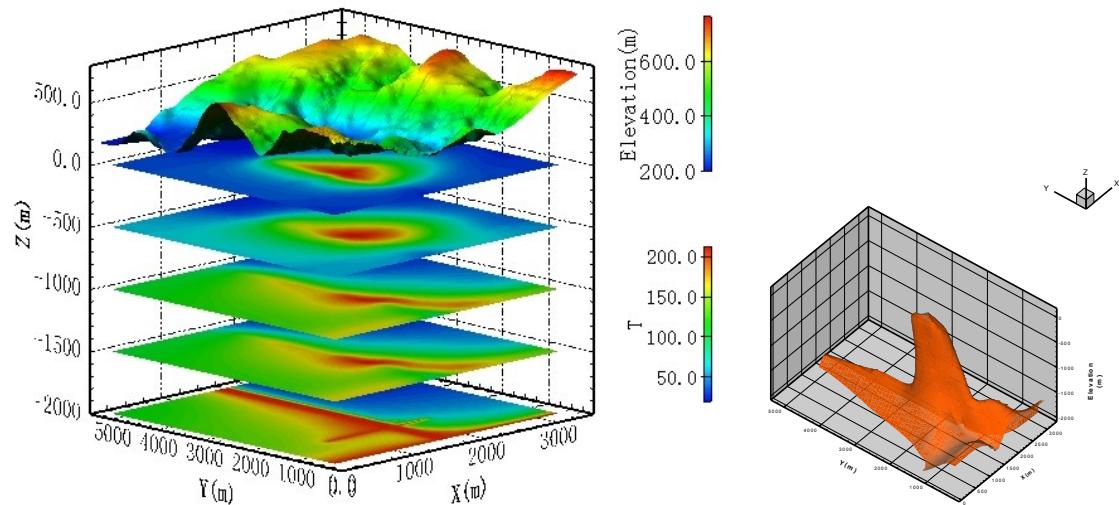


Figure 4: The 3D geothermal reservoir temperature distribution and 200°C isothermal surface

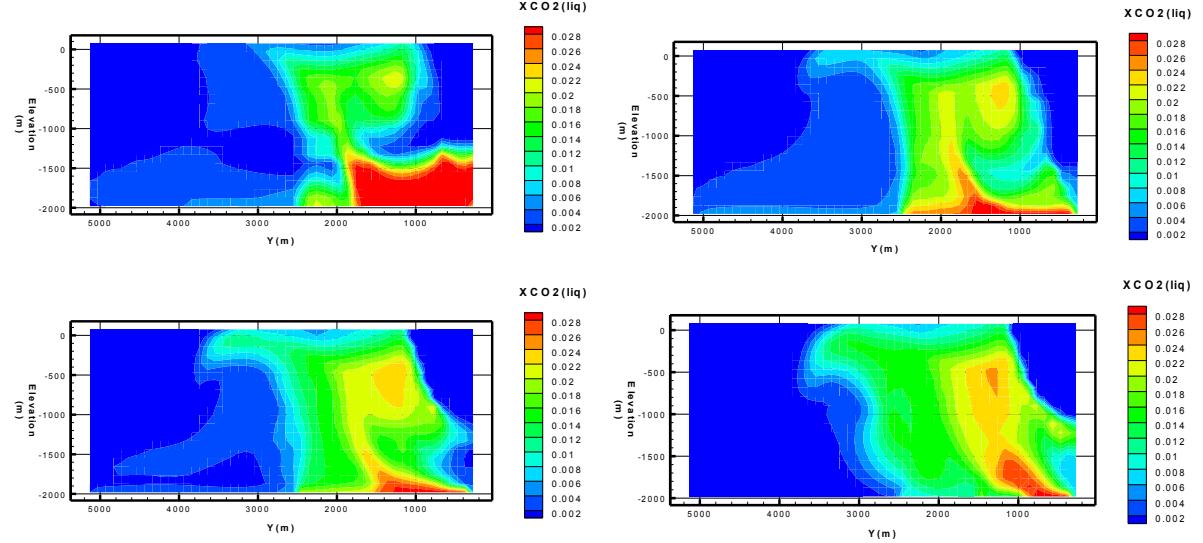


Figure 5: CO₂ mass fraction distribution at different vertical cross-sections

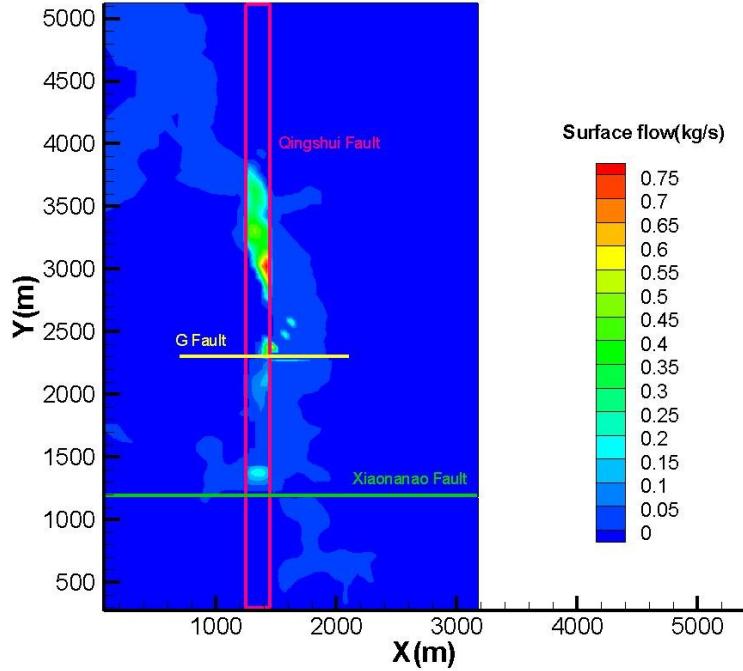


Figure 6: Simulated flux distributions at land surface

3. SIMULATION FOR PRODUCTION PERFORMANCE

The power plant for Chingshui geothermal reservoir (Lanyang power plant) was designed to generate 3MW power with steam/hot water produced from 8 production wells (IC-04, 05, 09, 13, 14, 16, 18, 19). The total average production rate of fluid was about 283 t/hr in the first year of operation. It decreased to 202 t/hr in the second year. The plant was decommissioned in 1993 due to continued decline in production. At the end of production, the total amount of steam/hot water produced from the 8 wells decreased to 42 t/hr.

The reasons for the production decline have not been fully understood. For better understanding of the performance, a model was designed to simulate response of the geothermal reservoir system to the production activities. A quantitative description of the fluid flow system in a geothermal reservoir will help greatly in evaluating geothermal reservoir performance. The steady-state solution of the calibrated natural-state model was used as a starting point to simulate the production history during 1981-1993. The total average production rate at each year was available. The production rate at each well was calculated based on historical exploitation records and the percentage of the maximum flow rate for each well. The missing production data for 1991 and 1992 were estimated by interpolation from information of previous years and year 1993.

In the model simulation, it was assumed that the fluid production was at a constant wellhead pressure. The actual production may have changed the wellhead pressure for better production rate. The assumption represents a conservative estimation of production capacity. Based on the hot water/steam flow rate in the first year of production, the wellhead pressure can be estimated through model calibration. The obtained well head pressure is then used for the whole 13 years' production operation.

Figure 7 shows the comparison of simulation result with the field record for production fluid rate change with time. Simulated production rate decreases dramatically at the first two years, and approaches to a steady rate after the third year. The model result shows that the production rate reduces from around 79kg / s at the first year to 57.2kg / s at the end of production, which is much less than the reduction of real production (from 79kg/s to 12 kg/s). The steady state rate is around 55kg/s. Reduction of production rate could be caused by several reasons. One of the possible reasons is by pressure drop in the reservoir or well head pressure increase. It is known that the wellhead pressure may change for a favorite production rate or does not change during the whole production period. Pressure drop in the reservoir could be caused by depletion of water sources or insufficient recharge of water to the reservoir system. Pressure drop in the reservoir will increase pressure gradient at the reservoir bottom boundary and lead to higher water recharge rate from the bottom boundary. In this modeling study, a constant recharge rate at the bottom boundary is applied and a constant wellhead pressure is used. A model with such assumptions may produce a conservative result (lower production rate). However, the simulated production rate is still much higher than real production at the site (Figure 7). This may indicate that the significant production reduction is not caused by the availability of water resources.

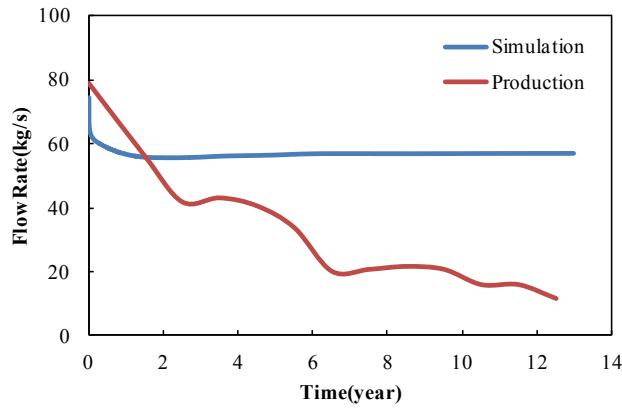


Figure 7: Compared flow rate between simulation and production data

In order to further confirm the conclusion, the model was run with doubling and halving water recharge rate at the bottom boundary. Simulation results indicate change of inflow rate brings only very limited impact on the well production rate. With the higher or lower inflow rate, well production capacity has less than 3% change. Simulation results show that the production rate is stable at 55.9 kg / s by cutting down the bottom inflow to half, which is about 2.2% lower than the original case. Taking consideration of the large reservoir domain and short production period, changes of inflow should have very limited impact on well production rate. We may conclude that the significant drop of the hot water production rate in the 13 years of power plant operation is not caused by the shortage of water resources at the site. However, the available water resources are not enough to maintain a production rate of 283t/hr. For conservative estimation, a sustainable production should be at a rate around 55 kg/s or 200 t/hr.

Previous studies showed that another potential cause that may lead to abnormal decrease of the production capacity is formation scaling. Chingshui geothermal reservoir production reduced from 79 kg/s to 12 kg/s in 13 years, which is not only due to the limitation of water sources or reservoir pressure drop, but also the formation scaling, which causes the reduction of formation permeability surrounding the wellbore. It was observed that fluid in the Chingshui geothermal reservoir contains a large amount of CO₂. When water is raised to the shallow formation, CO₂ will be released from the hot water due to the reduction of pressure and temperature. CO₂ release may cause water pH rising and calcium carbonate supersaturating, which will further lead to large amount of carbonate precipitation at wellhead, wellbore, and in fracture and porous space in the aquifer.

In order to investigate the impact of formation scaling on the production capacity, the numerical model was calibrated with variable permeability for formation surrounding the 8 production wells. By adjusting permeability near the production wells, the abnormal reduction of the production capacity can be easily simulated. It is assumed that permeability changes of all the wells are the same. Figure 8 shows the calibrated permeability for the eight production wells. It decreases from about 25 mD at the first year to 5 mD at the end of the production. Figure 9 shows the comparison of fluid production rate by simulation and real production. Fair match between the simulation and production may indicate good reasoning of the impact of scaling on decrease of production rate.

From the simulation studies, we may conclude that the abnormal drop of the reservoir production capacity is caused mainly by formation scaling. Through engineering efforts, it is possible to reduce scaling phenomenon. Once the scaling problem is solved, a sustainable production capacity of Chingshui geothermal reservoir is at a rate about 200 t/hr.

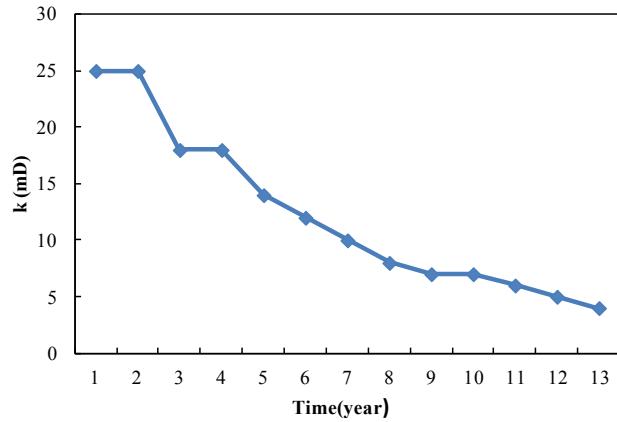


Figure 8: Permeability surrounding wellbore changed with time due to formation scaling

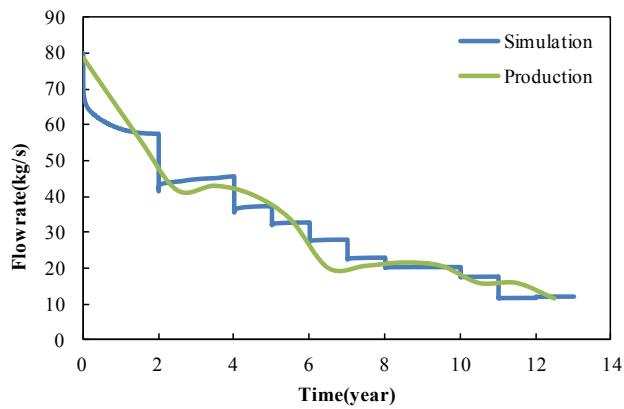


Figure 9: Fluid production rate matching of simulation and real production

4. CONCLUSIONS

A natural state model for the Chingshui geothermal reservoir has been developed. The model shows an excellent match between simulation results and field measurements at 16 wells. Consideration of the CO_2 component in the simulation may produce better prediction for the spatial distributions of temperature and pressure in the model domain. Simulation results indicate that the total fluid in the reservoir is about $1.23 \times 10^9 \text{ m}^3$, and the total recharge rate to the model domain is about $4.03 \times 10^5 \text{ m}^3/\text{year}$. From model results, it is obvious that the effluent flux distribution at the land surface is controlled mainly by Chingshui fault and G fault.

From the production model, we can conclude that the abnormal drop of the reservoir production capacity was caused mainly by scaling. The availability of water resources contributes only a limited impact on the decrease of production rate. With doubling or halving inflow rate at the bottom boundary, well production capacity has less than 3% change. If formation scaling can be avoided, it is expected that a sustainable production capacity of Chingshui geothermal reservoir could be at a rate of about 200 t/hr. Higher production capacity can be reached, if reinjection of the production water to the reservoir is considered.

5. ACKNOWLEDGEMENTS

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