PROCEEDINGS, Thirty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 9-11, 2009
SGP-TR-187

ASSESSMENT OF GEOTHERMAL POTENTIAL AT UNGARAN VOLCANO, INDONESIA DEDUCED FROM NUMERICAL ANALYSIS

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ABSTRACT

Ungaran volcano is located in the Central Java, Indonesia. Numerical analysis has performed in order to assess the geothermal potential of Ungaran volcano using a 3-D finite difference simulator HYDROTHERM Ver2.2. A conceptual model constructed based on the results of geophysical studies such as gravity, spontaneous-potential, micro-earthquake, infrared imagery and shallow ground temperature. Deep geothermal fluids have been supplied from below in the central part of the volcano, then change into a lateral flow; part of the geothermal fluid reaches to the ground surface and forms the Gedongsongo fumarole area. The background temperature distributions and mass flux patterns were calculated for 150,000 years to obtain the quasi-steady state. The meteoric water flow pattern demonstrates predominant downward flow, with mass flux varying between 10^{-8} g/cm^{2}sec up to 10^{-7} g/cm^{2}sec. The thermal evolution was calculated for up to 30,000 years. The deep geothermal fluids supplied from below in the central part of the volcano has an enthalpy of 1085 kJ/kg (250^{o}C) and a mass flow of 230 kg/s to 250 kg/s. In order to estimate the geothermal potential for conventional electric power production, we employed the minimum reservoir temperature is 150^{o}C and the performance of reservoir was predicted for 30 years production. Depths of the reservoir are assumed from 0.5 km to 3 km beneath mean sea level. As the result, the estimated geothermal potentials are 2.3 MW up to 40.4 MW depending on different thicknesses of the reservoir.

Keywords: Ungaran volcano, Indonesia, numerical analysis, assessment geothermal potential

INTRODUCTION

Ungaran volcano located in the Central Java province about 30 Km southwest of Semarang, Indonesia as shown in Figure 1, is still undeveloped geothermal prospect. There are some geothermal manifestations at the piedmont of Ungaran volcano. Gedongsongo is the main geothermal manifestation in Ungaran volcano, located in the southern part of the Ungaran volcano which several geothermal manifestations such as fumaroles, hot springs, hot acid pool and acid surface hydrothermal alteration rocks exist. In this study, a hydrothermal model of Ungaran volcano is presented using numerical simulation technique based on mass and energy balance equations, supported by the computer program HYDROTHERM 2.2. (Hayba and Ingebritsen, 1994). The objective of this study is to assess the geothermal potential of Ungaran volcano for conventional electric power production.

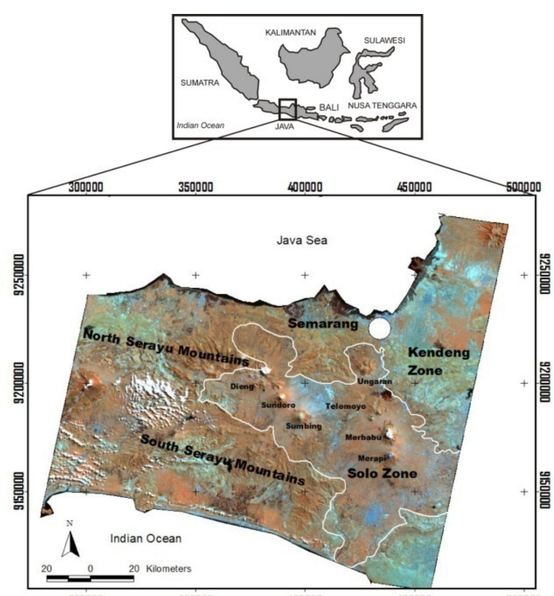

Figure 1: Location of the study area.

GEOLOGY

Ungaran is a complex volcano consisting of a younger body, which was formed by the most recent volcanic activity, and an older body formed by prior volcanic activity**.** The Young Ungaran body seems to have been constructed inside a caldera formed during the older Ungaran activity. According to Kohno et al. (2006), the Old Ungaran body formed prior to 500,000 years ago, and the Young Ungaran volcano did not form until 300,000 years ago. The volcanic rocks are rich in alkali elements and are classified as trachyandesite to trachybasaltic andesite. Ungaran volcanic area is composed of andesitic lava, perlitic lava, and volcanic breccia from the post Ungaran caldera stages, as shown in Figure 2 (Thanden et al., 1996). There are geothermal manifestations at the piedmont of Ungaran, namely Gedongsongo, Banaran, Kendalisodo, Diwak, Kaliulo, and Nglimut. Gedongsongo is the main geothermal feature associated with the Quaternary Ungaran andesitic volcanic complex. Moreover, a structural analysis of this area has revealed that the Ungaran volcanic system is controlled primarily by the occurrence of the Ungaran collapse structure running from the northwest to the southeast. Fault systems trending northwest to southeast and northeast to southwest control the old volcanic rocks of the pre-caldera formation.

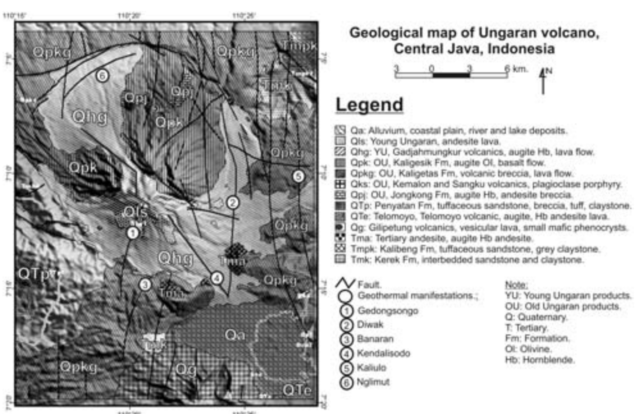

Figure 2: Geologic map.

CONCEPTUAL GEOTHERMAL MODEL

A model of underground geothermal fluid flows was presented based on the several geophysical surveys (Setyawan et al., 2008). The geophysical surveys consist of spontaneous-potential (SP), micro-earthquake, infrared imagery, and shallow ground temperature observations. SP data showed that the main upflow zone of geothermal fluid is situated at the central part of the volcano around the collapse wall and the lateral flow of geothermal fluid causes the geothermal activities at Gedongsongo area. Two hundred seventy events including four earthquake swarms were recorded during 4-day seismic observation in 2005, and the hypocenters are distribute located in a shallower region than 500 m around the collapsed wall. The total heat discharge rate from Gedongsongo area was estimated as 1.25 MW by using the infrared imagery and the hot springs data. The shallow ground temperatures exhibit negative trend with altitude and it shows that geothermal anomalies are only distributed around Gedongsongo fumarole area. The following conceptual model of hydrothermal system beneath Ungaran volcano was presented based on the geophysical, geological and geochemical data. Deep geothermal fluids are supplied from below in the central part of the volcano, then changes into a lateral flow; part of the geothermal fluid reaches to the ground surface and forms the Gedongsongo fumarole area.

GRID DESIGN AND BOUNDARY CONDITION

The numerical simulation covers an area of 21 km in a east-west direction, 11 km in a north-south direction as depicted in Figure 3. In order to absorb the boundary effect of the numerical model, we set the extra block and called the buffer areas. The buffer areas are set 10 km each lateral faces of the analytical area. The vertical cross section of the center edifice in slice No 18 of east-west direction was presented in Figure 4. The vertical pressure distribution is given as hydrostatic and the ground surface boundary pressure value is fixed at 1.013 bars. The hydrological boundary condition at the surface is assumed to be permeable. To set up constant-value and no-flow boundaries, HYDROTHERM uses the following convention for indexing blocks and allowing flow between blocks. In the input file, the user labels active blocks with sequential positive-integer values, constant blocks with -1, and inactive blocks with 0. Interface between active and inactive blocks are no-flow boundaries, as are the sides of active blocks that lie on the grid boundaries. Flow between constant blocks and an adjacent active block varies with the pressure/enthalpy conditions in the active block. According to the results of 2D modeling of gravity, we set two layers in Ungaran volcano; the first layer is lower density and the second layer is higher density. The detail setting of layer blocks: (-1) is constant blocks of 1st layer, (-2) constant block of 2nd layer, (1) is active blocks of 1st layer, (2) is active block of 2nd layer and (0) is inactive blocks, which also can be seen in Figure 4. The temperature (*T*) of the surface is according from the altitude point (*H*) following the empirical formula obtained by shallow ground temperature measurement of Ungaran on September 2007, which is followed by:

$T = 33.56^{o}C – 0.0084\ (^{o}C/m) \times H\ (m).$

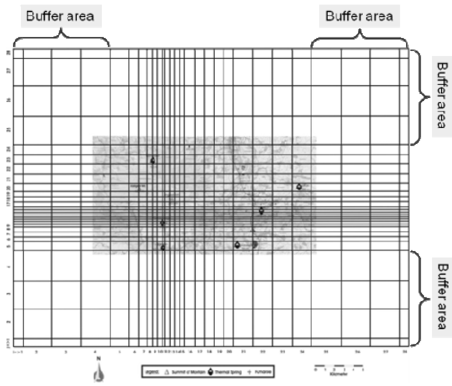

Figure 3: Horizontal extent of the study area which includes the buffer area whose width is 10 km at each lateral face and the total blocks are 28 in each direction.

The temperature of the subsurface increases with depth at the rate of 0.046^{o}C/m, which is obtained by $Q = - K (dT/dz)$, where Q is the constant heat flux of 120 mW/m^{2} in this simulation (Nagao and Uyeda, 1995) and K is the thermal conductivity of 2.6 W/mK. Unfortunately, the information of the physical parameters in Ungaran volcano is only the rock density until now. We adopted the other rock properties from the case of Merapi volcano as shown in Table 1. The reason is Merapi volcano located in the southern side of Ungaran volcano. There are many publications of Merapi volcano. Schwarzkopf et al. (2005) analyzed the lithologies/composition of the July 11, 1998 basal avalanche and found that its vesicularity ranged from 5% to 40% and that its specific heat was 1,350 J/kg K. Estimation of the porosity of the material of Merapi volcano, the values of about 10% to 20% is suggested by the results of gravity observations (Setiawan, 2003) and gravity inversion (Tiede et al., 2005).

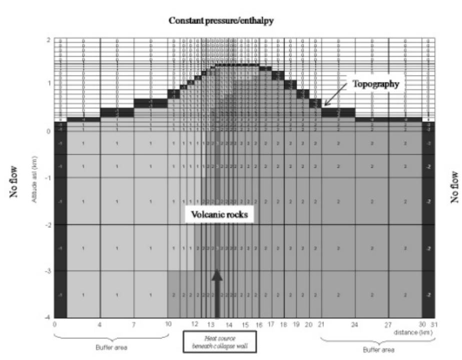

Figure 4: Vertical cross section of transient state in the S-N slice No.11. The heat source was set beneath the collapsed wall deduced from the micro-seismic observation, which is represented in layer 3 and indicated the high porosity and high permeability.

RESULTS AND DISCUSSIONS

Quasi-steady state

The steady model was constructed with the aim of obtaining the natural thermal state beneath Ungaran volcano without intruding any thermal source inside. We calculated the background structural model under the conditions mentioned in Table 1. The calculation time started from 100,000 years up to 150,000 years. The reason of such long calculation time was considered from the high topography of Ungaran volcano which affected the meteoric water circulation. Very longer time than 100,000 years was necessary for meteoric water to infiltrate into the deeper part. Finally we needed the calculation time of 150,000 years for the quasi-steady state to be obtained. Figure 5 shows the background temperature distribution and mass flux pattern calculated for 150,000 years. The meteoric water flow pattern demonstrates predominant downward flow, with a mass flux value varying between 10^{-8} g/cm^{2}sec up to 10^{-7} g/cm^{2}sec.

Transient state

The transient simulation model was constructed by using the pressure and temperature distributions from the quasi-steady state simulation as its initial conditions. We employed the transient simulation, in which the supply of geothermal fluid (temperature is 250^{o}C and enthalpy is 1085 kJ/kg) was assumed beneath the collapsed wall corresponding to the active seismic zone. Moreover, according to the result of the seismic observation, we set high permeability and high porosity to the layer 3 beneath the collapsed wall area as shown also in Figure 4 and the physical properties are shown also in Table 1. The thermal evolution was calculated for up to 30,000 years as shown in south-north direction (Figure 6). Up-flow of hot water occurs beneath the collapsed wall area, then the rising fluids move laterally and some portion of the fluid discharges at the surface in Gedongsongo area.

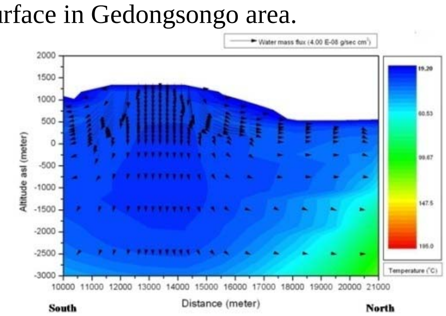

Figure 5: Background temperature distribution and mass flux patterns on the S-N slice No.11 calculated for past 150,000 years (steady state). The meteoric water flow patterns demonstrate the dominant downward flow.

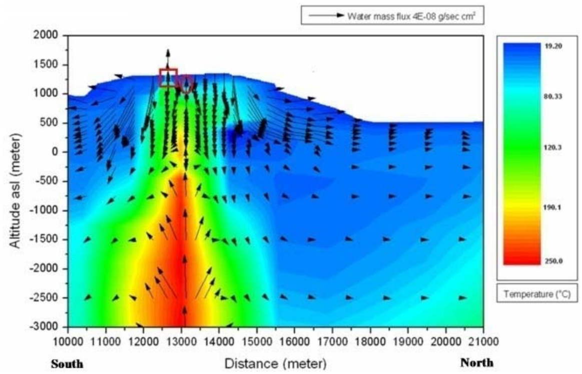

Figure 6: The S-N slice No.11, temperature distribution and mass flux pattern in transient state calculated after 30,000 years. The heat source beneath the collapsed wall area, which mass flux is 250 kg/s and enthalpy is 1085 kJ/kg. An up-flow of hot water occurs beneath the collapsed wall area (in the circle area) and some portion of the water discharges as the surface thermal manifestations (in the square area).

This result has a good correlation with the SP observation obtained in the study. Heat discharge rate is a matching parameter in this numerical study. Total heat discharge rate was calculated by adding the heat discharge from hot springs and conduction as illustrated by $Q_{Total} = Q_{hs} + Q_c$. The heat discharge from hot spring is expressed as $Q_{hs} = H \times q \times A$ and the heat discharge from conduction is followed as $Q_c = K \times \nabla T \times A$, where Q_{hs} is the heat discharge rate from hot spring (W), Q_c is the heat discharge rate from conduction (W), H is the enthalpy (kJ/kg), q is the mass flux (kg/m^2 sec) and A is the area of Gedongsongo of 6250 m^2, K is thermal conductivity of 2.6 W/mK, and ∇T is near surface temperature gradient at Gedongsongo area of 1.47 ^{o}C/m. Table 2 shows the calculated heat discharge rate from numerical simulations by fluid (hot spring) at Gedongsongo area, while the calculate heat discharged from conduction is 0.24 MW. Total heat

Rock properties	Value 1st layer	2nd layer	3rd layer
Porosity (%)	15	10	20
Permeability (m darcy)	20	2	100
Thermal conductivity (W/m K)	2.6	2.6	2.6
Specific heat (J/kg K)	1350	1350	1350
Density (kg/m^3)	2390	2640	2390
Constant bottom heat flux (mW/m^2)		120	

Table 1: Rock properties of the model.

discharge rates produced by the heat source with enthalpy of 1085 kJ/kg and mass flux between 230 kg/s up to 250 kg/s are 0.87 MW up to 1.67 MW, respectively. This result agreed well with the observe value of 1.25 MW.

ASSESSMENT OF GEOTHERMAL POTENTIAL OF UNGARAN VOLCANO

In order to assess the geothermal potential of Ungaran volcano for conventional electric power production, we employed the limited temperature of 150^{o}C and the performance of reservoir was assessed for 30 years production. The geothermal potential is estimate using the following formula (NEDO, 2005). The stored heat (kJ) is expressed as $SH = (T_r - T_f)\ \{(1-\varphi)\ C_{pr}\ \rho_r + \varphi C_{pw}\ \rho_w\}\ V$; *the* recovery heat (kJ) obtained by $HR = SH \times RF$ and $Output/hour = (HR \times CE) / (Lf \times PL)$. where T_r is reservoir average temperature (^{o}C), T_f is lower limit temperature (^{o}C), φ is porosity of rock (%), C_{pr} is specific heat of rock (kJ/kg^{o}C), C_{pw} is specific heat of fluid/water (kJ/kg^{o}C), ρ_r is density of rock (kg/m^3), ρ_w is density of fluid (kg/m^3), V is reservoir volume (m^3) which is calculated by adding the volume of each block which has the temperature of 150^{o}C or over, while the volume of each block is area x thickness, RF is recovery rate, equivalent with $2.5 \times \varphi$ (%), CE is conversion efficiency from heat to electricity (10%), Lf is availability factor of plant (85%) and PL is running period of plant (30 years). Unfortunately, the exact location of the reservoir in the study area is not clarified until now. Based on the result of the simulation, we make four assumptions for the location of the reservoir. The thicknesses of the reservoir are 0.5 km, 1 km, 2 km and 3 km beneath mean sea level. The estimated potentials are 2.3 MW, 7.2 MW, 19.7MW and 40.4 MW, respectively. Table 3 shows the estimation of the potential of Ungaran volcano for conventional electric power production.

From the above discussion, we estimated the region where the temperature is higher than 150^{o}C. If the reservoir temperature is lower than 150^{o}C, we suppose the area is for a binary system and direct use such as cold storage, space heating (building and greenhouses), drying of agriculture product, evaporation and canning of food, etc. Finally, we proposed a schematic geothermal model of Ungaran volcano deduced from the result of numerical model as presented in Figure 7.

CONCLUSION

We presented a numerical model of Ungaran volcano based on numerical simulation. The background temperature distributions and mass flux patterns were

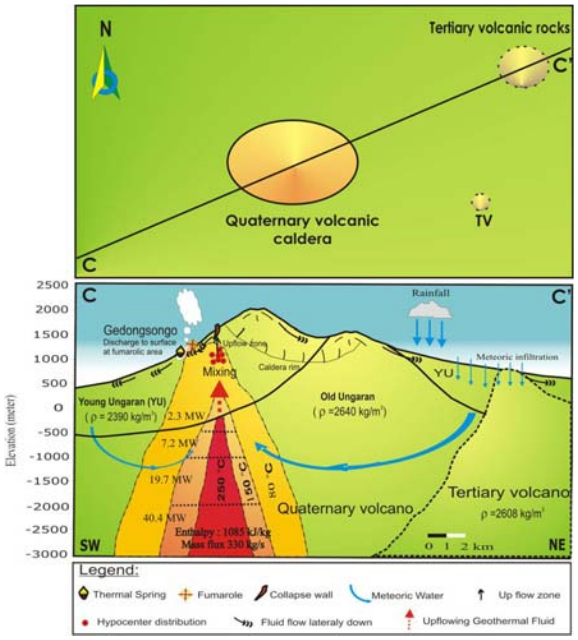

Figure 7: Proposed schematic hydrothermal fluid flow model of Ungaran volcano deduced from the numerical model.

calculated for 150,000 years to attain the quasi-steady state. The meteoric water flow pattern demonstrates predominant downward flow, with a mass flux value of 10^{-8} g/cm^2 sec to 10^{-7} g/cm^2 sec. The thermal evolution was calculated for up to 30,000 years. Up-flow of hot water occurs beneath the collapsed wall area, after that the geothermal fluids move laterally and then some portion of the geothermal fluids discharges at the surface in Gedongsongo fumarolic area. Based on the numerical simulation model, the geothermal potential of Ungaran volcano is estimated at 2.3 MW to 40.4 MW depending on the assumed thickness of the reservoir.

Heat-source		*Gedongsongo area*			
Enthalpy kJ/kg	*Mass flux* kg/s	*Enthalpy* kJ/kg	*mass flux* kg/m^2 sec	*Area* m^2	*Heat discharge* (MW)
1085	400	548.53	5.22E-04	6.25E+04	17.89
1085	375	548.53	4.57E-04	6.25E+04	15.65
1085	350	548.53	3.74E-04	6.25E+04	12.81
1085	345	548.53	3.57E-04	6.25E+04	12.22
1085	340	548.53	3.45E-04	6.25E+04	11.83
1085	335	548.53	3.23E-04	6.25E+04	11.07
1085	330	548.53	2.38E-04	6.25E+04	8.14
1085	325	548.53	2.21E-04	6.25E+04	7.58
1085	300	548.53	1.74E-04	6.25E+04	5.96
1085	250	548.53	4.16E-05	6.25E+04	1.43
1085	230	548.53	1.83E-05	6.25E+04	0.63
1085	225	548.53	1.37E-05	6.25E+04	0.47
1085	200	548.53	5.91E-06	6.25E+04	0.20

Table 2: Heat discharge rate in Gedongsongo area calculated from the numerical simulations.

ACKNOWLEDGMENTS

This study supported by a Grant-in aid for Scientific Research (B) No.17404024 from the Ministry of Education, Culture, Sports, Science and Technology of Japan, which acknowledged.

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Physical property	*Depths of the geothermal reservoir beneath Ungaran volcano*			
	(3 km)	*(2km)*	*(1 km)*	*(0.5 km)*
T_r is reservoir average temperature (^oC)	218	203	191	172
T_f is lower limit temperature (^oC)	150	150	150	150
φ is porosity of rock (%)	10	10	10	10
C_{pr} is specific heat of rock (kJ/kg^o C)	1.35	1.35	1.35	1.35
C_{pw} is specific heat of fluid (water) (kJ/kg^{o}C)	4.4	4.4	4.4	4.4
ρ_r is density of rock (kg/m^3)	2470	2470	2470	2470
ρ_w is density of fluid (kg/m^3)	900	900	900	900
V is reservoir volume (m^3)	5.6E+9	3.5E+9	1.6E+9	1E+9
Storage Heat (S.H) (kJ/kg m^3)	1.3E+16	6.3E+15	2.3E+15	7.5E+14
Potential of Ungaran volcano for power generation (MW)	40.4	19.7	7.2	2.3

Table 3: Geothermal potential estimation of Ungaran volcano for conventional electric power production.

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